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OAK RIDGE
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MARTIN MARIETTA

ENERGY TECHNOLOGY R&D: WHAT COULD MAKE A DIFFERENCE?

A Study by the Staff of the
Oak Ridge National Laboratory

Part I: Synthesis Report

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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ENERGY TECHNOLOGY R&D: WHAT COULD MAKE A DIFFERENCE?

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IEA	Institute for Energy Analysis
LANL	Los Alamos National Laboratory
LBL	Lawrence Berkeley Laboratory
LLE	Laboratory of Laser Energetics
LLNL	Lawrence Livermore National Laboratory
NRL	Naval Research Laboratory
PPPL	Princeton Plasma Physics Laboratory
SERI	Solar Energy Research Institute
SNLA	Sandia National Laboratories-Albuquerque
UT	The University of Tennessee

Contents

LIST OF FIGURES xi
LIST OF TABLES xiii
SOME ENERGY UNITS AND OTHER HELPFUL CONVERSIONS xv
LIST OF ACRONYMS xvii
ACKNOWLEDGMENTS xix
ABSTRACT xxi
PREFACE xxiii
EXECUTIVE SUMMARY xxv

1. INTRODUCTION AND APPROACH 1
   1.1 FLOW OF ENERGY IN SOCIETY 2
   1.2 APPROACH 2
   1.3 ORGANIZATION OF THE REPORT 6

2. THE ENERGY SYSTEM IN 1988 9
   2.1 THE WORLD BEFORE 1973 9
   2.2 THE WORLD AFTER 1973 12
      2.2.1 Energy End Use 18
      2.2.2 Energy Sources 20
   2.3 INTERNATIONAL CHARACTER OF ENERGY 31
   2.4 FUTURE ENERGY DEMAND 32
   2.5 ENERGY SYSTEM PROBLEMS - CURRENT AND EXPECTED 40
      2.5.1 Environment, Health, and Safety Issues 40
         2.5.1.1 Global consequences of energy use 41
         2.5.1.2 Multinational consequences of the energy system 48
         2.5.1.3 National consequences of the energy system 49
         2.5.1.4 Local and regional consequences of the energy system 54
         2.5.1.5 Individual (or family) level consequences of the energy system 55
      2.5.2 Energy Insecurity and Fluctuating Oil Prices 56
      2.5.3 The Needs of Developing Countries 57
      2.5.4 Lack of Public Confidence in Nuclear Power 57
   2.6 CHARACTERISTICS OF A DESIRABLE ENERGY SYSTEM 59

3. THE R&D OPTIONS 61
   3.1 PROMISING ENERGY TECHNOLOGY R&D OPTIONS 68
      3.1.1 Energy End-Use Technology 68
         3.1.1.1 Transportation 68
         3.1.1.2 Buildings 70
         3.1.1.3 Industry 71
         3.1.1.4 Electricity 73
         3.1.1.5 Advanced conversion to electricity 73
         3.1.1.6 Storage 75

3.1.2 Energy Sources 75
3.1.2.1 Petroleum 75
3.1.2.2 Natural gas 75
3.1.2.3 Coal 76
3.1.2.4 Nuclear power 77
3.1.2.5 Fusion 79
3.1.2.6 Biomass 79
3.1.2.7 Solar electric 80
3.2 CROSSCUTTING TECHNOLOGIES AND AREAS OF SCIENCE 81
3.3 COMPARISON WITH UNITED KINGDOM STUDY 83
3.4 ENERGY TECHNOLOGY R&D THAT CAN MAKE A DIFFERENCE 86

4. A BALANCED ENERGY TECHNOLOGY R&D STRATEGY 87
4.1 THREE FUTURE CIRCUMSTANCES 88
4.1.1 Circumstance 1 88
4.1.2 Circumstance 2 89
4.1.3 Circumstance 3 89
4.2 PROBLEMS, FUTURE CIRCUMSTANCES, AND A BALANCED STRATEGY 96
4.2.1 R&D Options and Energy System Problems 98
4.2.1.1 Environment, health, and safety issues 98
4.2.1.2 Energy insecurity and price fluctuations 99
4.2.1.3 Energy needs of less-developed countries 99
4.2.1.4 Problems with nuclear power 99
4.2.1.5 Summary: problems and options 100
4.2.2 Future Circumstances and R&D Options 100
4.2.3 New Opportunities 100
4.2.4 Balancing the current R&D agenda 105
4.3 SUMMARY 110

5. PRINCIPAL CONCLUSIONS AND GENERAL OBSERVATIONS 111
5.1 PRINCIPAL CONCLUSIONS 111
5.2 GENERAL OBSERVATIONS 112

REFERENCES 117

APPENDIX A. R&D OPPORTUNITIES IDENTIFIED IN THE SUPPLY AND END-USE AREAS A-1

APPENDIX B. R&D OPPORTUNITIES IDENTIFIED IN THE CROSSCUTTING AREAS B-1

APPENDIX C. REDUCING CO_2 EMISSIONS C-1

List of Figures

1.1	Flow of energy in U.S. society in 1987	3
1.2	Energy expenditures as a percentage of Gross National Product	4
1.3	Top-down and bottom-up approaches to analysis used in the study	5
2.1	Historical trends in oil prices	12
2.2	Total primary energy consumption in the United States (1929-1987) and the ratio of energy use to Gross National Product	13
2.3	Apparent efficiency of energy use continues to increase	14
2.4	Efficiency gains have moderated growth in energy demand	14
2.5	Primary energy consumption per capita	15
2.6	World oil consumption and world oil production capacity	15
2.7	Change in world oil prices versus utilization of OPEC production capacity	16
2.8	Effect of oil price shocks on real compensation per hour in the U.S. business sector	17
2.9	Potential impacts of DOE energy conservation R&D on projected energy use in the year 2010	20
2.10	World oil resources as of Jan. 1, 1985: cumulative production, identified reserves, and undiscovered resources of crude oil by region	21
2.11	Resources of fossil fuels in the United States and in the world	22
2.12	World crude oil supply as projected by Chevron	23
2.13	Oil price outlook as projected by Chevron	23
2.14	World gas resources as of Jan. 1, 1985: cumulative production, identified reserves, and undiscovered resources of natural gas by region	24
2.15	GRI baseline projection of supply of gas	25
2.16	Solar cell production and costs	28
2.17(a)	Comparison of forecasts of total energy consumption in the United States.	34

LIST OF FIGURES (*continued*)

2.17(b) Comparison of forecasts of the ratio of energy consumption and GNP in the United States 35

2.18 Alternative projections of global energy use by industrialized and developing nations 37

2.19 Alternative projections of global energy use by source 39

2.20 Primary energy consumption for the high efficiency scenario 40

2.21 Primary energy consumption for the middling scenario 41

2.22 Carbon dioxide emissions for the middling and high efficiency scenarios 42

2.23 Surface warming due to greenhouse gases 44

2.24 Global average temperatures over the past 100 years 46

2.25 Hypothetical future oil price fluctuations 58

4.1 Primary energy use by various nation groups: Organization of Economic Cooperation and Development (OECD) nations, U.S.S.R. and East Europe, and the rest of the world 90

4.2 Oil use by various nation groups and the world 91

4.3 Estimated potential of efficiency increases and nonfossil energy sources for reducing U.S. CO_2 emissions from fossil fuel combustion 95

4.4 Projected CO_2 emissions for various nation groups assuming various growth rates 97

4.5 Combined energy technology R&D budgets (DOE, EPRI, GRI, and USNRC) 107

4.6 Percentages of combined energy technology budgets (DOE, EPRI, GRI, and USNRC) by technology 108

C.1 Relative CO_2 emissions by various nation groups C-2

List of Tables

S.1 Energy technology R&D options of greatest promise xxvii

S.2 Crosscutting technologies xxxi

S.3 Current and imminent environment, safety, and health problems and issues related to the energy system xxxiv

S.4 The importance of R&D options to achieving or accommodating the three future energy circumstances xxxvii

S.5 Additional energy technology R&D expenditures needed to be prepared to control CO_2 emissions (combined public and private sector investments) xxxix

2.1 U.S. and world primary energy use and associated CO_2 emissions 10

2.2 Apparent reductions in energy intensiveness of end-use sectors in the U.S. economy, 1973-1983 19

2.3 Estimated remaining recoverable resources of fossil fuels and their potential effect on atmospheric carbon dioxide 26

2.4 CONAES energy demand scenarios 33

2.5 Factors affecting energy growth to 2020 37

2.6 Comparison of potential health risks to the total U.S. population from the nuclear and coal fuel cycles [per GWy(e)] 50

2.7 Correspondence between desirable energy system characteristics and criteria used in Chap. 3 to evaluate energy technology R&D options and areas 60

3.1 Criteria for selecting top R&D opportunities 62

3.2 Promising energy technology R&D options 64

3.3 Evaluation of promising R&D options 65

3.4 Crosscutting technologies and related areas of science 69

3.5 Promising R&D options identified by Oak Ridge National Laboratory and the Department of Energy, The United Kingdom 84

4.1 Potential reduction in U.S. CO_2 emissions via efficiency improvement and/or nonfossil energy sources assuming energy technology R&D successes 94

LIST OF TABLES (*continued*)

4.2 Relative importance of promising R&D options for coping with or achieving the three future circumstances 101

4.3 Fiscal year 1988 energy technology R&D budgets (DOE, EPRI, GRI, and USNRC) . . 106

C-1. CO_2 emissions, 1977-87 (GtC/year) and average growth rates (%/year) C-3

C-2. Assumed contributions of nonfossil sources C-5

Some Energy Units and Other Useful Conversions

1 Btu	1054.8 Joules	
	2.93×10^{-4} kWh	
1 barrel of petroleum	$\sim 5.8 \times 10^6$ Btu	
1 metric ton petroleum	$\sim 42 \times 10^6$ Btu	
1 metric ton petroleum	~ 7.3 barrels of petroleum	
1 cubic foot of natural gas	~ 1030 Btu	
1 ton of coal (U.S. average)	$\sim 22 \times 10^6$ Btu	
1 metric ton of coal (U.N. standard coal equivalent)	$\sim 27.8 \times 10^6$ Btu	
1 quad	10^{15} Btu	
1 quad	1.055×10^{18} Joules = 1.055 EJ	
1 quad	~ 0.47 million barrels oil per day	
1 quad of oil	~ 0.02 GtC	CO_2 emissions as 10^9 metric tons of carbon
1 quad of coal	~ 0.025 GtC	
1 quad of natural gas	~ 0.015 GtC	

List of Acronyms

ABWR	advanced boiling water reactor
AFBC	atmospheric fluidized-bed combustion
AGA	American Gas Association
ALWR	advanced light water reactor
APWR	advanced pressurized water reactor
atm	atmosphere (pressure)
bbl	barrel
BES	Basic Energy Sciences
°C	degrees Celsius
CAFE	Corporate Average Fuel Economy
CFCs	chlorofluorocarbons
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CONAES	Committee on Nuclear and Alternative Energy Sources
COP	coefficient of performance
CPE	centrally planned economies
DISC	direct injection stratified charge (engine)
DOE	(U.S.) Department of Energy
E/GNP	total energy use divided by gross national product
EH&S	environment, health, and safety
EIA	Energy Information Administration
EOR	enhanced oil recovery
EPP	Energy Policy Project
EPRI	Electric Power Research Institute
ER	Edmonds-Reilly (model)
ERDA	Energy Research and Development Administration
°F	degrees Fahrenheit
FGD	flue gas desulfurization
FY	fiscal year
gal	gallon
GBR	gas-cooled breeder reactor
GNP	gross national product
GRI	Gas Research Institute
GtC	gigatons of carbon
GTID	geologically targeted infill drilling
GW(e)	gigawatt (electric)
HG	historical growth
HVAC	heating, ventilating, and air-conditioning
IGCC	integrated gasification combined cycle
IIASA	International Institute for Applied Systems Analysis
ISTIG	intercooled steam-injected gas turbine
kWh	kilowatt hour

LHR	low heat rejection
LMFBR	liquid metal fast breeder reactor
LNG	liquefied natural gas
LWR	light water reactor
MBD	million barrels per day
MCF	million cubic feet
MCFC	molten carbonate fuel cell
MHTGR	modular high temperature gas cooled reactor
MITI	(Japanese) Ministry of International Trade and Industry
MPG	miles per gallon
MW(e)	megawatt (electric)
NAAQS	National Ambient Air Quality Standards
NAPAP	National Acid Precipitation Assessment Program
NAS	National Academy of Sciences
NEPP	National Energy Policy Plan
NIMBY	"Not In My Back Yard"
NRC	National Research Council
NO_x	nitrogen oxides
N_2O	nitrous oxide
O_3	ozone
OOIP	original oil in place
OECD	Organization for Economic Cooperation and Development
OPEC	Organization of Petroleum Exporting Countries
ORNL	Oak Ridge National Laboratory
OTA	Office of Technology Assessment
PAFC	phosphoric acid fuel cell
PFBC	pressurized fluidized bed combustion
PIUS	process-inherent ultimately-safe (reactor)
ppm	parts per million
PRA	probabilistic risk assessment
PRISM	power reactor inherently safe module
PURPA	Public Utilities Regulatory Policies Act of 1978
quad	quadrillion (10^{15}) Btu
R&D	research and development
RD&D	research, development, and demonstration
ROW	rest of the world
SAFR	sodium advanced fast reactor
SOFC	solid oxide fuel cell
SPR	Strategic Petroleum Reserve
SO_2	sulfur dioxide
STIG	steam-injected gas turbine
TAHP	thermally activated heat pump
TCF	trillion cubic feet
TF	technical fix
TMI	Three-Mile Island
TVA	Tennessee Valley Authority
USNRC	U.S. Nuclear Regulatory Commission
WEC	World Energy Conference
ZG	Zero Energy Growth

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Bill Fulkerson
Project Manager
May 1989

Abstract

The objective of this study was to survey both energy technologies and crosscutting areas of science and technology in order to identify important R&D needs and opportunities in the context of the U.S. and world energy situations. The imperative for R&D was judged against its potential for fixing current energy system problems; for providing a robust set of options for coping with, taking advantage of, or encouraging future energy circumstances; and for creating unanticipated opportunities.

The principal conclusions were

1. The energy technology R&D effort of the country should be and is broad in scope. Breadth is needed because of large uncertainties about future energy demand, especially demand for oil, and about the consequences of the greenhouse effect and other environmental health and safety problems. Fossil fuels will still likely dominate the U.S. and world energy systems 50 years from now unless concern about the greenhouse effect intervenes.

2. Although aggregate public and private sector R&D is sufficiently broad-based, it is inadequate for providing longer-term options to cope with the greenhouse effect. Nonfossil energy sources individually and collectively are not yet ready to substitute massively for fossil fuels, and providing better technologies will require long lead times. Correcting this inadequacy will probably require an additional R&D investment of about $1 billion per year.

3. The R&D prospects appear bright for producing much improved nonfossil sources, ranging from passively safe nuclear power reactors to less expensive photovoltaics. Hence, making the needed additional investment seems a small risk and good insurance. Little is likely to be lost even if the greenhouse effect turns out to be less important than some fear since better nonfossil sources will be useful in their own right.

4. The technical potential for economical improvements in the efficiency of energy use is large, and an expanded R&D effort can increase the potential significantly. Realizing this potential is the best near- to mid-term strategy for moderating the growth of CO_2 emissions. Furthermore, the strategy should be attractive to all nations since it can also save money, enhance competitiveness, reduce the stress on the oil market, and reduce environmental impacts of energy sources, including those from global warming. However, the rate and extent of adoption of more efficient and economical technologies depend on many factors and are highly uncertain.

5. Part of this added R&D investment should be to provide new or adapted technologies tailored to the needs of developing nations since the energy choices of developing nations will be crucial in determining the future of the greenhouse effect and the demand for petroleum as well.

Preface

Energy technologies have been improved remarkably since the Arab oil embargo of 1973-74, and current R&D efforts promise further significant improvements, ranging across the energy system from sources to end use. The progress in many areas is rapid, and the energy technology outlook is changing, owing in part to spectacular advances in related areas of science and crosscutting technologies such as biotechnology, microelectronics and computing, and materials science (e.g., high-temperature superconductors). It seems timely, therefore, to review the evolving state of the technology and to include in the appraisal the potential future impacts on energy technologies of the many developments in the science and crosscutting technology areas.

This study, commissioned by the management of the Oak Ridge National Laboratory (ORNL), identifies promising areas of R&D that may make significant beneficial differences in the future energy situation. The goal is to help ORNL management in reviewing existing priorities and setting new ones for the Laboratory.

The study was conducted largely by more than 100 ORNL staff members from all across the Laboratory with some important help from some colleagues in other R&D institutions. The participants, listed at the beginning of this document, were mostly volunteers; the effort they expended was in addition to their regular duties. Everyone knew this constraint from the outset, and yet the level of interest was most intense, which is a strong indication that what we tried to do was worthwhile.

Although the initial intent was that the study serve the needs of the senior managers of the Laboratory and the ORNL staff, particularly those who participated, we received much advice, information, and insight on technology R&D progress and promise from our colleagues around the country. Some have helped peer review the product. Hopefully the document will be of use to them as well. Finally, we hope that the study will be of value to managers in the Department of Energy (DOE) and perhaps even to the new administration.

Our work will be published in two volumes. This synthesis report (Vol. 1) views energy technology R&D broadly in the context of the energy situations of the United States and of the world. Volume 2, organized into three parts, contains more detailed reports. Part 1 concerns end-use technologies. Various energy source and conversion technologies are reviewed in Part 2, and Part 3 is a review of R&D opportunities and needs in various crosscutting areas of science and technology.

The U.S. energy technology R&D community is complex, pluralistic, decentralized, and compartmentalized. Consisting of many players, this community includes universities; DOE, its laboratories, and contractors; the Electric Power Research Institute (EPRI), the Gas Research Institute (GRI), and their contractors; numerous state agencies, such as the New York State Energy Research and Development Agency, the California Energy Commission, and the Florida Solar Energy Center, to name but a few; and, of course, research establishments in private firms producing energy resources and technologies. Funding for R&D comes from the government, from the private sector, from tariffs on utility operations, and more and more frequently from foreign governments and companies.

In this multifaceted arena, it is not a trivial problem to know what is happening or even what has happened. This study is meant to help keep the ORNL staff up to date with these multiple R&D activities and to put the various pieces of R&D into the overall context of the energy situation.

Of course, various studies by others have addressed the state of energy technology R&D. These include, for example, some 18 reports by the Office of Technology Assessment (OTA) of the Congress over the past 8 years on various energy technologies and policy issues. Currently, an integrative OTA study, *Technological Risks and Opportunities for Future U.S. Energy Supply and Demand*, is in progress. The state of technology and various technology R&D issues is assessed from time to time by the Energy Research Advisory Board of DOE and by the National Research Council. In addition, various ad hoc assessments have been made;

and some of them are updated periodically as parts of the planning activities of the organization funding or performing R&D. We have tried to take maximum advantage of what others have done or are doing. Most of all, we have tried to talk to people around the country who are doing R&D.

Executive Summary

Two major uncertainties preclude gaining a clear picture of future energy technology needs: (1) future energy demand and (2) the seriousness and urgency of the greenhouse effect and of other environmental, health, and safety problems. To allow for these uncertainties, it is important to have an R&D strategy that is balanced with respect to its focus on improved energy sources and its focus on improved end-use energy efficiency.

Whatever the future holds, developing economical technologies which use energy more efficiently is an attractive R&D objective in both the short term and the longer term. Improving the efficiency of energy use and conversion can help solve many problems facing the U.S. and world energy systems. It can reduce the costs of providing energy services, it can contribute to international competitiveness, and it has high value in managing environmental impacts and improving energy security. However, despite the large and generally unanticipated efficiency improvements achieved by the United States and other industrialized nations over the past decade and a half, and although the technical opportunities for further improvements are substantial, the rate of future progress is uncertain. Social barriers and market imperfections may slow the adoption of more efficient technologies. For this reason, and to help correct existing problems with the energy systems and to avoid anticipated future ones, it seems imperative that there be significant improvement in energy supply technologies and especially in nonfossil sources. Hence, a balanced R&D strategy is required in order to improve both energy sources and end-use technologies.

In this study, we have surveyed a broad range of energy supply and end-use technologies with respect to problems, opportunities, and responsiveness to perceived societal needs. Our survey reveals a rich variety of R&D options all across the energy system which, if pursued, can achieve the needed balance. There exists in the United States at present a diversity of energy technology R&D activities that meet the broad, qualitative requirements for a balanced strategy. However, given the fundamental importance of energy to the economy, the level of R&D expenditures from both public and private sources, amounting to only 1 to 1.5% of total annual energy expenditures, seems too low. Furthermore, the existing set of activities is inadequate for coping with the greenhouse effect. None of the nonfossil energy sources, separately or collectively, is ready to substitute for fossil fuels at the necessary large scale and with the performance, cost, and social acceptance required to be competitive. Consequently, a much more intensive R&D effort is required to develop and improve nonfossil sources which will be required for any sustained control of CO_2 emissions. Similarly, a greater R&D investment is needed to develop technologies that will improve the efficiency of end use and conversion of fossil fuels, since improving efficiency is the most effective near-term strategy for reducing CO_2 emissions. We estimate that the annual energy technology R&D investment by the country (both public and private) would need to be increased by about $1 billion to correct the inadequacy.

This increased R&D investment is an insurance policy with relatively small risk since the potential for success seems large and the resulting improved technologies will be useful, even if the greenhouse effect turns out to be less consequential than many fear.

S.1 OBJECTIVE AND APPROACH

Our objective in this report is to provide Oak Ridge National Laboratory (ORNL) management and staff with a broad-based review of energy technology R&D in the belief that such a review will be useful as people think about the energy situation and energy technologies and as they make decisions about R&D priorities. A second objective is to educate ourselves and perhaps thereby to strengthen our dedication to helping solve the energy problems of the nation and the world through R&D. This second objective was pursued by involving some 100 staff members from all across the Laboratory.

The question "What Could Make a Difference?" was examined from two directions. First, technical promise and need were considered. That is, can significant technological advances be made within a reasonable time and cost? Also, what important national needs can be met by R&D that significantly improves an energy technology? This is a bottom-up, or technology-push, look at R&D opportunities. The other direction, top-down, or demand-pull, concerns the potential importance of the R&D to the energy system. Looking from both national and international perspectives, we tried to identify what could make a difference for the nation as a whole, leaving aside the question of whether the R&D is more appropriately sponsored by the federal government or by the private sector, including the Gas Research Institute (GRI) and the Electric Power Research Institute (EPRI).

Both energy technologies and crosscutting areas of science and technology were reviewed. Energy technologies included (1) end uses for each sector and the technical conditions that influence end uses, such as the design of building envelopes; (2) the primary sources, fossil and nonfossil; and (3) energy carriers, (e.g., electricity and hydrogen). Crosscutting areas of science and technology were those judged to have a significant impact on energy technology. These included materials; biotechnology; microelectronics, computing, and sensing; combustion; separations; effluent management; geosciences; and management and decision making. The last was felt to be important because of the applicability of the growing science of organizational decision making and conflict resolution to energy technology issues. The technical reviews of the energy technologies and the crosscutting areas comprise Vol. 2 of this report.

Our study looks at needs and opportunities over the next 50 years. Thus, it looks at technologies that may be available in the near term as well as those that may not come on line for decades. We considered it important to use a 50-year time frame because some important R&D may take decades and because near-term decisions both on R&D and on deployment of energy technologies can have long-term consequences. Thus, a sense of possible energy circumstances in the longer term should be most helpful in making judgments even about near-term R&D priorities. A sense of where we might be headed and where we might want to head should help us make better R&D choices.

S.2 RESULTS AND CONCLUSIONS

S.2.1 R&D That Could Make A Difference

Each of the technical reviews recorded in Vol. 2 identifies energy technology R&D opportunities and needs which, in the judgment of those authors, are significant. (A list of options is given in Appendix A of this volume.) Many of these are already a part of the R&D agenda of the nation. In fact, the reviews were influenced strongly by the research activities and plans of the U.S. Department of Energy (DOE), EPRI, and GRI. Of course, ORNL plays a strong role in some of these.

In this synthesis report (Vol. 1), the R&D options described in Vol. 2 are evaluated for their potential contributions to improving the U.S. energy system. Clearly, there is no perfect energy source. A source may have a limited resource base (e.g., oil and natural gas), may cause significant environmental damage (coal), may pose safety concerns (nuclear), may be very expensive (solar), or may require action by many people to be implemented widely (efficiency improvements*). For the energy technology R&D options we studied, their potential

*Efficiency improvement is not an energy source but it has the effect of reducing the demand for primary sources.

for reducing these liabilities and improving the system was evaluated against a set of 16 criteria in 6 categories: (1) energy significance—amount of energy produced or saved; (2) economics and international competitiveness; (3) environmental, health, and safety impacts; (4) energy security in terms of oil; (5) social impacts—influence of the new technology on the social infrastructure and its acceptability to the public and the investment community; and (6) impacts on less-developed countries. Some 50 energy technology R&D options were chosen from this screening as being particularly promising and are listed in Table S.1.

This evaluation process was generally qualitative and judgmental. Other analysts using the same process could arrive at different lists. Nevertheless, the results and their justifications were reviewed extensively, both internally and externally, and these reviews influenced the final choices. The list in Table S.1 includes significant options from across the energy spectrum, including fossil and nonfossil sources and all the end-use sectors. The results reveal a great richness in the opportunities; and in almost every area, the reviews indicated the potential for substantial technical progress with R&D.

In addition, significant crosscutting R&D opportunities and needs were identified during the technical reviews reported in Vol. 2. Many have a direct bearing on the energy technologies listed in Table S.1, and some of these connections are summarized in Table S.2. Again the richness and promise are impressive, and further progress in these crosscutting areas of science and technology should lead to unanticipated but rewarding opportunities in the energy technologies.

S.2.2 A Balanced Energy Technology R&D Strategy

The bottom-up approach that we used to identify and evaluate promising R&D options ensured broad coverage of the whole energy technology R&D arena. Each of the 50 options we selected is currently the subject of some R&D activity and collectively they provide comprehensive coverage of important energy sources and end uses. However, the bottom-up approach provides no basis for assigning emphasis to one or another of the options. In order to get a better perspective on appropriate R&D emphasis, we therefore carried out the top-down review of the R&D options.

Table S.1. Energy technology R&D options of greatest promise

Transportation efficiency

- *Advanced automotive engine technologies*: efficient gas turbines and low-heat-rejection (LHR) reciprocating engines are promising technologies which require improvements in high-temperature materials and lubrication, and attention to the adequacy of combustion and emission control as well. Continued improvement in smart fuel injection systems and, more broadly, combustion enhancing technologies will benefit conventional engines and may permit the use of unthrottled engines in spark-ignited versions, perhaps with LHR, for light-duty, light-fuel (gasoline, methanol) applications with notably improved efficiency and low emissions.
- *Continuously variable transmission*: permits optimum operation of engines
- *Automated dynamic traffic control*: smart systems can optimize traffic flow and reduce fuel use
- *Improved aircraft efficiency*: composites, plastics, and light alloys may simplify manufacture while saving weight; more efficient by-pass engines should be economical without sacrificing performance; improvements in design and materials should reduce drag; and better operations control should offset increased congestion

Table S.1 (*continued*)

Building efficiency

- *Heat pumps*: major potential gains from more efficient electric and gas-fired equipment
- *Lighting*: more efficient lamps as well as optimum control to meet lighting needs have significant potential
- *Smart control systems—sensors and controls*: precise determination of energy needs and control to reduce waste
- *Envelopes*: heat losses can be sharply reduced with advanced materials and system design
- *Manufactured buildings and components*: economic method of construction that promises significant energy benefits if innovative concepts are included
- *Computer-assisted design for efficiency and cost control*: very economic energy reduction in new buildings; immediate payoff that will continue to grow
- *Existing building retrofits*: improving predictions of energy savings and how building occupants affect energy use will promote cost-effective retrofits

Industrial energy efficiency

- *Catalysts*: improved catalysts can reduce energy requirements of many chemical processes
- *Sensors and controls*: improve process efficiency by precise delivery of exact energy needs using intelligent sensors
- *Separations*: developments include membranes, supercritical fluid extraction, and improvements to distillation with much lower energy requirements
- *Advanced heat management*: optimization of heat flows by improved monitoring and control, high temperature heat pumps, recuperators, and storage can reduce losses substantially
- *Cogeneration*: steam-injected aeroderivative turbines, fuel cells, and other innovations make continuing progress likely for both industry and large building applications
- *Pulp and paper processes*: integration of fermentation into the conventional pulping process promises significant energy savings
- *Steel processes*: advanced steelmaking processes can reduce energy use by 50% as well as increase productivity
- *Agricultural techniques*: new plants and new techniques for cultivation and harvesting promise to reduce requirements for energy as well as for water and fertilizer

Electricity applications

- *Superconductor applications*: great improvement in the efficiency of motors, transmission lines, etc., if the new materials prove feasible
- *Power electronics*: efficient control of motors and other electrical devices

Advanced conversion to electricity

- *Aeroderivative gas turbines* (intercooled steam-injected gas turbine, etc.): low cost, very efficient; may be technology of choice for electric generation if gas is available or when coupled to coal or biomass gasification

Table S.1 (*continued*)

Advanced conversion to electricity (*continued*)

- *Brayton cycle*: high-temperature gas turbine combined-cycle utilizing MHTGR should yield 45-50% efficiency in electricity production
- *Kalina cycle*: possible 50% efficient conversion for combined gas turbine and kalina steam/ammonia turbine cycles if capital costs can be reduced
- *Fuel cells*: very efficient electric generators with low NO_x emissions if gas is available, but cost and longevity are uncertain
- *Hot gas cleanup*: key to high-efficiency gasification of coal and biomass

Petroleum

- *Enhanced oil recovery*: major opportunity for increasing oil availability as oil prices increase
- *Field characterization techniques*: extend use of enhanced oil recovery and optimize infill drilling

Natural gas

- *Exploration and drilling techniques*: new gas fields (e.g., deep gas) at moderate cost
- *Unconventional gas techniques*: potentially major increase in gas supplies at moderate price; could keep gas an option for many decades (e.g., from tight formations)

Coal

- *Oil substitutes*: coal-water mixtures and micronized coal can provide a relatively easy replacement for industrial use of oil; advantages for fluidized bed combustion
- *Fluidized bed combustion*: economic and environmental advantages for both utility and industrial coal combustion
- *Bioprocessing*: economically desulfurized coal and potential breakthroughs in gasification and liquefaction
- *Gasification*: key to greatly expanded use of coal as a replacement for natural gas and perhaps oil
- *Liquefaction*: most likely way to replace large quantities of oil

Nuclear fission

- *Improving light water reactor (LWR) technology*: substantial energy contribution from increased availability of existing plants and improved public acceptance from incident-free, high-productivity operation; advanced LWR technology could reduce cost and incorporate passive safety features
- *Modular high temperature gas reactor*: advanced concept featuring passive safety should enhance public acceptance; standardized modular design; potential for very high efficiency and process heat applications; could be crucial for CO_2 reduction
- *Liquid metal fast breeder reactor*: important option for ensuring long-term fuel supply; urgency of need will increase if concern about greenhouse effect leads to large-scale nuclear deployment; passive safety features need to be proven

Table S.1 *(continued)*

Nuclear fission *(continued)*

- *Waste management techniques*: implementing a waste management plan based on public participation and consensus is necessary for public health and a prerequisite for a nuclear revival

Fusion

- *Fusion power*: inexhaustible, CO_2-free energy source (with potential for relatively small environmental impacts); long development program but should provide valuable spinoffs; magnetic fusion R&D international in character
- *Fissile fuel breeder*: uses fusion technology to produce fuel for fission reactors

Biomass

- *Feedstock development*: increased plant productivity can make biomass a significant liquid energy source; new sources of energy (e.g., hydrogen and oil from algae)
- *Conversion technology*: fermentation, other direct liquefaction techniques, and gasification (indirect liquefaction) tailored to feedstock species are keys to biomass derived transportation fuels to replace fossil fuels
- *Municipal solid waste processing*: produce energy from recycled materials while reducing landfill problems

Solar electric

- *Photovoltaic energy conversion*: cost breakthroughs possible; already economic for some applications; small packages with appropriate storage could be future technology of choice, especially if CO_2 is a problem
- *Solar thermal*: may be cheaper than photovoltaics but is more complex and lacks market niches to grow in
- *Hydroelectric*: methods to realize 50 GW(e) additional capacity focus on analysis and minimization of environmental effects to fish and other aquatic life
- *Wind turbines*: power electronics, better materials, and improved aerodynamics should lead to significant cost reductions

Storage

- *Advanced batteries*: key to electric vehicles and photovoltaics
- *Thermal storage*: new materials, some using chemical processes or phase changes, could improve solar thermal economics and intermittent industrial processes

Table S.2. Crosscutting technologies

Microelectronics and sensors

- Smart systems for control of industrial processes, combustion efficiency, building heating/cooling/lighting, etc.
- Sensors for determining conditions in harsh environments

Advanced materials

- Ceramics for high-temperature engines
- Surface treatments, including low-friction materials
- Superconductors for motors, power electronics, and transmission lines
- Materials by design
- Lightweight structural materials
- High-temperature, erosion- and corrosion-resistant materials for hot gas cleanup, turbines, heat exchangers, etc. in harsh environments

Biotechnology

- Improved plants for high biomass productivity
- Microbes for coal cleaning, oil recovery, and hydrogen production
- Genetic engineering of improved enzymes

Separations

- Improved distillation
- Membranes
- Supercritical fluid extraction
- Low-grade ore recovery (including recovery from seawater)

Combustion science

- Efficiency improvement and environmental control of internal combustion engines and boilers
- Enhanced fuel switching capability
- Municipal waste incineration

Geosciences

- Improved understanding of reservoirs for enhanced oil recovery
- Gas exploration techniques
- Unconventional gas recovery

Table S.2 (*continued*)

Geosciences (*continued*)

- Categorizing and evaluating geothermal energy resources
- Waste immobilization and isolation

Effluent management

- Waste reduction and recycling
- Pollution control techniques for improving the efficiency of transforming and scavenging harmful effluents
- More manageable waste forms (stable and degradable)

Decision making and management

- Planning for technologies involving social risk (e.g., more effective mechanisms for public participation in decision making)
- Managing the reduction in the emissions of CO_2
- Implementing high energy efficiency strategies
- Utility least-cost planning
- Planning for uncertainties

A balanced R&D strategy should not only provide generally improved energy technologies but also facilitate the attainment of three societal objectives. First, it should help solve existing or imminent energy system problems. Second, it should provide a robust set of options for coping with, taking advantage of, or encouraging future energy circumstances. That is, it should help move the system in desirable directions, and it should provide insurance against adverse circumstances. R&D should, in short, provide technological resilience for an uncertain future. Finally, R&D provides the important function of creating unanticipated opportunities. Part of any balanced energy technology R&D strategy should be basic, generic and crosscutting research which has a chance to produce breakthroughs that can revolutionize energy technology (i.e., the type of R&D outlined in Table S.2). In fact, some of the opportunities identified in the review of crosscutting areas influenced the choices listed in Table S.1.

Neither energy system problems nor our guesses about future energy circumstances are independent of our selection of promising R&D options. As mentioned, system problems and desirable characteristics were used to select criteria against which to evaluate the R&D options. Still it is useful to examine problems and future circumstances from the top down, which can give a different perspective of R&D needs.

S.2.2.1 Strengths and problems of the energy system in 1988

The global and U.S. energy systems are both reasonably healthy. They have proven to be resilient over the past decade and a half despite the magnitude of the oil price shocks. Significant adjustments have occurred in both supply and demand, but the speed and extent of the adjustments in energy end-use patterns (e.g., the success of efficiency improvement and conservation, particularly in the United States and other industrialized countries) were largely unanticipated. Few would have predicted in 1974, for example, that the United States would be using about the same amount of primary

energy in 1987 as it did in 1973, even though the economy grew 39% in real terms during that period.

The adjustments made were both institutional and technical. Significant institutional changes included the following: Oil and gas markets were largely deregulated; the Strategic Petroleum Reserve was organized and developed (and now contains 550 million barrels); various efficiency standards were adopted, (including the Corporate Average Fuel Economy standards for automobiles and light trucks, appliance standards, and building codes); utilities became active in helping customers use energy more efficiently; and energy R&D was institutionalized with the formation of EPRI and GRI and in the federal government—first with the Energy Research and Development Administration and then DOE. Also, on the institutional side, the United States maintained and expanded its efforts to improve the protection of human health, safety, and the environment; in fact, regulations which impact the energy system became substantially more stringent.

Technological adjustments were also substantial. Throughout the system, we discovered how to use fuel more efficiently, and we became much more clever at fuel switching. For example, we learned how to make vehicles more efficient and with less emissions, and substantial progress was made in burning coal more efficiently and cleanly. The opportunities for further technological advances through R&D are enormous; and, as summarized above, we have identified many possibilities across the energy system which could make a difference.

These adjustments in the energy system, although effective, were not made easily, inexpensively, or smoothly. The oil price shocks caused or exacerbated two recessions and caused or contributed to regional economic depressions. Additionally, the energy problems of the country probably worsened the human displacement impacts of the major industrial restructuring that is now under way.

The components of the energy system have changed more than the total system over the past 15 years, but these individual changes have not been dramatic. The system is still dominated by fossil fuels but less so (down from 96% in 1973 to 89% in 1987), primarily because of the growth of nuclear-supplied energy, which is up from 1% of the total to 6%. The energy system is also still oil dominated, although not as much as 15 years ago (43% compared with 47%). The world is not running low on fossil fuels, not even oil and gas. Indigenous U.S. resources of fossil fuel, particularly coal and oil shale, are enormous and should be sufficient to last much longer than 50 years, even with substantially increasing demand. The same is true worldwide. However, most accessible and inexpensive oil and gas reserves are not in the United States—hence our growing dependence on foreign sources, some of which are in unstable parts of the world. Nonfossil energy sources do not yet compete strongly with fossil fuels for many uses, particularly transportation. Therefore, it is reasonable to expect that the U.S. and world energy systems will still be dominated by fossil fuels 50 years from now, just as they were 50 years ago (barring a technological breakthrough in nonfossil sources or decisions to control use of fossil fuels because of concern about greenhouse effects).

Despite the present relative health of the energy system, significant problems and uncertainties, current or imminent, persist and are relevant to an energy technology R&D strategy. Four problems are particularly important:

1. ***Impacts of the energy system on the environment and human health and safety.*** Concern about these impacts is growing in both industrialized and developing nations. Table S.3 is a listing of some of these energy-related environmental, health, and safety issues.
2. ***Energy insecurity and price instability.*** As oil prices have dropped, consumption has started to increase again, and oil imports have moved sharply upward, perhaps setting the stage for future price shocks. Also, the rate of increase of energy productivity, as measured by the decline in the ratio of primary energy use to Gross National Product (GNP) seems to be slowing. A loss of energy productivity may adversely affect U.S. competitiveness with other countries (e.g., Japan).
3. ***Energy needs of less-developed countries.*** Improving the economic condition of less-developed countries is vitally important to maintaining world economic and political stability and on moral grounds. Reasonably priced energy services will be essential to improvement. In addition, the rapidly growing demand for primary energy sources by developing nations can

Table S.3. Current and imminent environment, safety, and health problems and issues related to the energy system

Global consequences of energy use

- *The greenhouse effect*: a potential show stopper for fossil fuels
- *Stratospheric ozone depletion*: chlorofluorocarbon substitutes are needed
- *Nuclear accidents and proliferation of nuclear fissionable material*: what happens anywhere in the world impacts nuclear power everywhere

Multinational consequences

- *Acid rain*: will drive the development of cleaner coal technologies

National consequences

- *Environmental, health, and safety risks of fuel cycles*: all primary sources have undesirable impacts of one kind or another which may be the objects of national concern and regulation

Local and regional consequences

- *Smog (ozone) and carbon monoxide*: could promote the development of alternate fuels and vehicles
- *Land and water resources*: important factors in the choice of energy sources (e.g., solar, biomass, near-surface coal, and oil shale)
- *NIMBY ("Not in my back yard")*: this syndrome epitomizes the decision making problem for many new energy facilities

Individual (or family) level consequences

- *Indoor air pollution*: an important design constraint in new high-efficiency buildings and in retrofitting older ones
- *Automobile safety*: a potential barrier to improving vehicle efficiency through weight reduction

put additional stress on the environment at all geographic scales.

4. ***Problems with nuclear power.*** Advances are needed to demonstrate improved reactor performance and enhanced safety using simpler passive systems and for acceptance of a plan for nuclear waste storage and disposal.

S.2.2.2 Three future circumstances

Two major uncertainties about the energy future complicate the selection of an appropriate energy technology R&D agenda. One is the growth of demand for fossil fuels, particularly oil and gas. Sustained economic growth is a societal goal, not

any particular level of energy use. As population and wealth grow, the demand for energy services will increase. The experience of the past 15 years has shown that economic growth can occur without increase in the demand for primary energy sources if the efficiency with which energy services are delivered increases sufficiently or if shifts in the industrial sector toward less energy intensive products and processes occur. Efficiency can continue to improve, but lower oil and gas prices reduce the incentives. We do not know how effectively efficiency improvement will proceed in the future.

The second uncertainty is environmental. We do not know the extent to which environmental, health, and safety problems may cause curtailment of particular energy sources or uses. Potentially, the most serious of these problems is the greenhouse effect caused by increasing concentrations of CO_2 and other infrared-absorbing trace gases in the atmosphere. The principal causes of increasing CO_2 levels are anthropogenic, primarily the burning of fossil fuels and land use changes, notably deforestation. If the consequences of the greenhouse effect become serious, the impact on the energy system could be profound.

These uncertainties led us to consider three future circumstances which might imply quite different requirements for energy technology R&D.

Circumstance 1 (high efficiency, low oil use). Improvement in the efficiency of energy use and reduction of oil use are emphasized and practiced by the United States and many other countries to the extent that it is economically attractive to do so. Demand for primary energy, particularly oil, grows much less rapidly than GNP, possibly even resulting in total primary energy use being held constant. Low or zero energy growth would depend on improvements (through R&D) in the technology of end use and conversion, on continuation of the trend away from energy intensive manufacturing processes, and on institutional measures that help or encourage (but do not coerce) people and organizations to optimize their energy consumption (in an economic sense). In this circumstance, such procedures are deemed appropriate to help cope with the externalities of environmental degradation and energy insecurity. To the extent that it works, this circumstance is ***highly desirable.*** It is a circumstance driven by improved technology, not austerity or curtailment. Up to a point, efficiency improvement can be the least-cost approach to providing the energy services required for economic growth, and it can contribute to our competitiveness. It also reduces the stress on oil and gas resources and provides more time to develop and improve nonfossil sources, to learn to extend indigenous oil and gas resources, and to convert and use abundant coal more cleanly and cheaply. Finally, it reduces many of the stresses that energy supply puts on the environment. To the extent that efficiency improvements are achieved worldwide, greenhouse impacts are slowed. Pursuing high efficiency through the development and use of technologies which provide energy services at economically competitive costs with equal or better performance than those for which they substitute is a no-loss strategy.

Circumstance 2 (increasing primary energy demand). Circumstance 2 results if Circumstance 1 is not obtained. In this circumstance, primary energy demand, particularly for oil, grows substantially faster than in Circumstance 1 for the same growth in the economy. Possible reasons are that improvements in the technology of end use and conversion occur at a slower pace, energy sources become cheaper, or market imperfections and institutional barriers which impede the adoption of improved end-use technology persist to a greater degree.

It should be emphasized that we do not know the extent to which a low energy future will in fact prove to be economically optimal. Nor do we know how closely the system will be able to approach the optimum, whatever it is, with the removal of market imperfections and institutional barriers. Furthermore, we do not know what might be the costs or social difficulties of the removal. Whatever the reason for its occurrence, Circumstance 2 requires significantly greater supplies of primary energy than are required for Circumstance 1.

Circumstance 3 (environmental concerns curtail fossil sources). Environmental, health, and safety concerns may lead to more or less severe restrictions on various forms of energy supply and use. In Circumstance 3, the consequences of the greenhouse effect are considered to be so severe that the use of fossil fuels must be curtailed. This circumstance would lead to the most profound change in the energy system. It would require urgent implementation of nonfossil sources, as well as more draconian

measures to enforce the adoption of more efficient technologies and the switch to fossil fuel substitutes in end uses including transportation. Biomass (for transportation fuels) and nuclear and possibly solar electricity would become crucially important.

These three circumstances are not either/or alternatives. Instead they represent boundaries, themselves somewhat arbitrarily defined, for the possibilities in which the energy system must operate, moving more toward one or another over time.

S.2.2.3 Elements of a balanced energy technology R&D strategy

In our view, a balanced energy technology R&D strategy must seek to provide a variety of new and improved technologies which form a robust set, in the sense that they help achieve or cope with the three possible future circumstances. The strategy should also help solve existing or imminent problems with the energy system and should promote development of new opportunities presently undreamed of. Consequently, the broad elements of the strategy are clear and seem almost trivially obvious. They are to conduct R&D in the following areas:

- improving the efficiency and flexibility (fuel switching capacity) of energy use and conversion technologies;
- improving fossil fuel sources by technologies which reduce environmental, health, and safety impacts and which extend and improve the availability and flexibility of indigenous resources;
- developing and improving technologies for nonfossil sources; and
- developing relevant areas of science and crosscutting technology, notably those listed in Table S.2.

Progress in all these areas is essential to the continuing health of our energy system. None, in our opinion, should be neglected. Obviously, the relative emphasis will change among the areas as circumstances change, including the progress of technology itself. The promising R&D options listed in Table S.1 populate each of these four elements, but the emphasis may change as the energy system moves toward the possibilities represented in the three circumstances. The relative emphases are indicated in Table S.4.

Improving the efficiency and flexibility of energy end-use and conversion technologies has high importance in all three circumstances. Improving fossil sources is generally given low emphasis for Circumstance 3, of course, and it is most important in Circumstance 2. Developing and improving nonfossil sources is essential for Circumstance 3 but is of low to moderate importance for circumstance 1. For Circumstance 2, nonfossil R&D is important insofar as it promises to be clearly competitive with fossil fuel costs. However, the improvement of existing nuclear power plant performance is important for all three circumstances. The current problems with a source that generates 18 to 20% of our electricity are too important to ignore, and the technical wherewithal to fix them seems attainable.

Our R&D strategy bears a striking resemblance to what the country is doing already, indicating that what may have appeared to be an unfocused collection of R&D efforts is, in fact, quite responsive to the nation's needs. Our polycentric and decentralized system has led to a broad-based R&D program which is exploring, at one level or another, most of the promising R&D opportunities we have identified.

Although the current U.S. energy technology R&D agenda is appropriately broad, is it adequate? Total R&D expenditures, public and private, are probably in the vicinity of $4 billion to $5 billion annually, or about 1 to 1.5% of total annual energy expenditures. For such a vital part of the economy, this percentage for R&D seems low. We have no absolute scale on which to judge, however, except to ask whether we are doing the research necessary to solve energy systems problems and to provide options for future circumstances.

We conclude we are not ready to cope with Circumstance 3. Nonfossil sources are just not good enough, including nuclear power—the only nonfossil source which could presently be mobilized worldwide at sufficient scale and reasonable cost to offset the growth of fossil fuel use. From this point of view, the nation's R&D agenda is not adequate nor balanced. A much greater effort is needed to develop and improve nonfossil sources and to improve the efficiency and economics of end-use technologies. The latter has the greatest potential to reduce

Table S.4. The importance of R&D options to achieving or accommodating the three future energy circumstances

Elements of a balanced energy technology R&D strategy	Three future circumstances 1[a]	2[b]	3[c]
• Improve efficiency and flexibility of energy use and conversion for			
- Transportation	H[d]	H	H
- Industry	H	H	H
- Buildings	H	H	H
- Electricity generation	H	H	H
• Improve fossil fuel sources			
- Clean coal technologies	H	H	L
- Extend oil and gas resources	H	H	M
- Synthetic liquid and gaseous fuels	H	H	L
• Develop and improve nonfossil sources			
- Improve nuclear power			
Better performance of existing system and LWR technology	H	H	H
Second-generation passively safe reactors	H	H	H
Resources extension	L	M	M
- Enhance biomass productivity and conversion	M	H	H
- Improve solar electric, wind, and hydroelectric			
Develop remaining hydroelectric	M	M	M
Reduce cost of solar electric	L	M	M
Reduce cost of wind turbines	L	M	M
- Demonstrate fusion	L	M	M
• Develop relevant areas of science and crosscutting technology	H	H	H

[a]Circumstance 1 — high efficiency, low oil use.
[b]Circumstance 2 — increasing primary energy demand.
[c]Circumstance 3 — environmental concerns curtail fossil sources.
[d]H = high importance of doing R&D in the time frame of this study; M = medium; L = low.

the use of fossil fuels in the near to mid term. Furthermore, as we have noted, the adoption of high-efficiency technology will provide more time to develop the needed improved nonfossil sources.

Reducing the nation's CO_2 emissions from current levels while maintaining economic growth will be very difficult to accomplish over the next 50 years. A reduction can be achieved only by a combination of much improved efficiency of fossil use and a greatly accelerated use of nonfossil sources. Our most optimistic estimate is that this combination might lead to an emission rate for the U.S. in the 2020-2040 time frame of about one-third the 1987 value of 1.3 GtC/year. This optimistic estimate is based on the assumption that primary energy demand can be kept in the range of 60 to 90 quads and that nonfossil sources can supply 40 to 70 quads.

The principal nonfossil sources are biomass*, providing 20 quads (which is converted to 10 quads of liquid fuel); nuclear power, providing an equivalent of 16 to 40 quads; and hydroelectric and other renewables, which supply 6 to 10 quads. The nuclear contribution is assumed to be based on a second generation of reactors with passive safety features.** The estimates of biomass and other renewable sources assume the development of much more economic technologies.

Holding primary energy demand near today's levels will require an average annual reduction of E/GNP at the same rate that GNP grows over the 50-year period. Whether such an improvement in efficiency can be achieved is unclear, but the likelihood of success will be increased if improved end-use and conversion technologies are developed. Also, we do not know how fast GNP will grow.

We cannot predict when the greenhouse effect will have a major impact on energy policy, but we believe that sooner or later it must. Substantially higher CO_2 concentrations in the atmosphere may be acceptable, but at some level further increases will, we expect, have unacceptable consequences. Because of the substantial lead time required, it seems imprudent to delay the R&D necessary to provide the options that move the energy system away from fossil fuels at reasonable cost. Furthermore, what will we have lost by taking aggressive action now? We will have learned how to be more efficient, a highly desirable outcome no matter what the future circumstance. We also will have learned how to make nuclear power safer and hopefully more acceptable and how to make solar and other renewable sources more economically competitive. We will have accelerated determining the feasibility of fusion. These outcomes will be useful in any event, and the cost of achieving them on an accelerated schedule is the increased cost of R&D.

What might this cost be? To get a ballpark number, we postulated expanding efforts on end-use and conversion efficiency, nuclear, solar (and other renewables), and fusion. We also believe an R&D program aimed at improving efficiency and developing nonfossil sources in less-developed countries should be part of the package. A rough guess is that the added cost would be about $1 billion annually, as itemized in Table S.5. This is similar to the effort that is called for in legislation proposed recently by Senator Timothy Wirth of Colorado and his colleagues (U.S. Congress 1988a). The public sector share of the cost might be derived from a very small tax on fossil fuel use. A tax rate as little as 0.2% would raise about $600 million per year. The private sector contribution could come from matching funds invested by private firms participating in the R&D. Their reward would be marketable technology.

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*Burning of biomass or biomass-derived fuels produces CO_2 emissions, of course, but growing the biomass removes CO_2 from the atmosphere so the cycle can be operated at steady-state with no net effect on the atmosphere.

**Our assumption here is that the expansion of nuclear power in the United States much beyond present levels will be acceptable only if a reactor technology relying more on passive safety features is developed. The first of these would be advanced LWRs available by the mid 1990s. Fully passively safe reactors such as the MHTGR would be available for commercial deployment by 2005.

Table S.5. Additional energy technology R&D expenditures needed to be prepared to control CO_2 emissions (combined public and private sector investments)

R&D area	Added cost ($ million per year)
Improve efficiency and economics of end-use and conversion technologies Phased increase over several years to double the current national level seems warranted by opportunities.	300
Improve nuclear power Prototyping an advanced LWR (ALWR) with passive safety features and an MHTGR which is fully passively safe would probably cost $3 billion to $4 billion over the next decade. Prototyping the liquid metal breeder with passive safety features should be initiated in the first decade of the next century.	300-400 (average)
Solar and renewables Expanded budgets for biomass, hydroelectric (to capture 50 GW of remaining capacity), photovoltaics, solar thermal electric, wind, and others (phased increases over several years) seem warranted by the technological promise.	200
Fusion Better international coordination of the $1 billion to $2 billion per year expended worldwide is needed.	No additional required if improved world cooperation achieved
Technologies for less-developed countries This would be the U.S. part of a worldwide effort to develop energy technologies for developing nations.	100-200
TOTAL	900-1100

Chapter 1
Introduction and Approach

Energy is an essential nutrient of the economies and social systems of nations. Such services as transportation, space conditioning, lighting, communications, food, industrial output, and some recreations are accurately characterized as energy services. Technology is the vehicle that society uses to convert primary energy sources into these services. The objective of energy technology research and development (R&D), then, is to provide a broader range of energy services that not only offer enhanced performance and reliability but also minimize the negative impacts on human health, safety, and the environment. Consequently, continuous innovation to produce new and improved technologies* is critical to our ability to shape the future of the energy system and thus the society.

As used in this report, technology is defined broadly. We believe technology must be seen as a set of man-machine systems. It includes that broad set of measures, techniques, and processes needed to ensure that energy services are delivered in a form which assures that human health, safety, and the environment are adequately protected. Technology, with rare exceptions, involves both software and hardware. The use of technology to convert primary energy into energy services occurs in the context of political, economic, and institutional systems; those systems, as well as the availability of natural resources, have always had—and certainly in the future will have—major impacts on the energy situation. This study has as its goal looking at technology as a broad activity that functions within a broader social resource context. Thus, energy technology R&D includes social science research to provide the knowledge and means to improve the management of energy systems.

Our faith is that R&D can provide the technology needed to ensure attractive alternatives for the United States and the world. Whether the country will have the resolve to do the research and the wit to use intelligently the technology developed depends on all of us. Nevertheless, we are cautiously optimistic—optimistic because of the promise of technology and the scientific progress that supports it and cautious because potentially serious problems loom, such as continued instability of oil markets, the potential for international conflict, and global environmental problems.

*We should try to be clear about what we mean by improved technology. What we mean is technology which supplies an energy service with equal or better performance than that which it replaces for lower life cycle cost or which supplies that service with better performance for a competitive life cycle cost (i.e., the increased performance is worth the increased cost as judged in the market place). For example, an automobile with the same acceleration, comfort, interior space, and safety as one it competes with in the market but with lower life cycle cost due to improved fuel economy is an improved technology. Another example would be an advanced nuclear reactor with the same life cycle cost as the present light water reactors but with walk-away passive safety. A new technology which provides a previously unavailable energy service is also what we mean by improved technology.

It should be kept clearly in mind that improved technologies are not free. The research, development, and demonstration (RD&D) required to bring them to the market has a cost. The trick is to choose RD&D with a benefit-to-cost ratio greater than unity. In this study, we have not attempted to estimate such a benefit-to-cost ratio, primarily because the benefits are difficult to quantify.

Also, we neither have today nor do we see much prospect for any single energy source technology which is without serious limitations. For this reason, the recent Japanese study published by the Ministry for International Trade and Industry is entitled *The Twenty-First Century Energy Vision: Entering the Multiple Energy Era* (MITI 1987). In that report, the authors recognize that there is no unambiguously preferred technology. Many source and end-use technologies and potential technologies are worthy of continued exploration, development, and improvement. Clearly, however, we cannot support R&D on every possibility with equal intensity. Which ones deserve the most attention? Our objective is to shed some light on this question.

The same question was the object of a recent comprehensive evaluation of energy technology R&D in the United Kingdom (U.K. DOE 1987), which concluded that a broad-ranging R&D program was warranted. Some comparisons between the results of the British study and ours are presented in Chap. 3.

Over the past two decades, the United States has moved from a low level of energy R&D in all but the nuclear area to a virtual explosion, including vigorous work on every conceivable R&D option, and then recently to a reduced but broad-based package of energy R&D activities pursued at a relatively relaxed pace. The current situation reflects the oil glut and declining prices of the mid-1980s, which caused both the private and public sectors to scale back R&D. In both sectors, however, energy continues to be a source of concern and a generator of problems. The continuing broad range of R&D activities is driven by those concerns and problems.

In this chapter, we summarize the technological components of the energy system from sources to end uses by briefly examining the flow of energy in society. We then describe the approach we took to analyze and evaluate energy technology R&D needs and opportunities, and we conclude by explaining the organization of the remainder of the report.

1.1 FLOW OF ENERGY IN SOCIETY

Figure 1.1 is a schematic representation of the flow of energy in the United States for 1987. It shows quite vividly the relative importance of the various primary sources (petroleum, natural gas, coal, nuclear power, hydroelectric power, and others). It also shows the conversion losses in the system due to transforming primary energy sources to more convenient carriers (e.g., electricity).

As the economy grows, energy services can be expanded by increasing either primary energy supply or the thermodynamic efficiency of conversion and end-use processes. Over the years since the Arab oil embargo of 1973-74, a controversy has raged over which of these approaches is likely to be more effective in the future; and they have often been treated as mutually exclusive instead of complementary. In fact, whole neo-religious cults have grown around these two methods of providing increased energy services. We profess to being in neither camp, but we have been influenced by the arguments of both. R&D can increase the effectiveness of either; and we assume that a prudent society, when faced with future uncertainty, must ensure R&D progress across the entire spectrum of energy supply, conversion, and end-use technologies.

The energy system diagrammed in Fig. 1.1 is a huge enterprise. As shown in Fig. 1.2, annual energy expenditures equaled about 8% of the U.S. gross national product (GNP) in 1987, or about $376 billion; they were as high as 13.5% of GNP in 1980 and as low as 7.6% in 1972.

A major portion of the energy supply is provided by large, costly physical facilities (e.g., electric power plants and refineries) that are operated for decades. Many of these facilities are managed by large organizations which generally change slowly. Some end-use technologies (e.g., automobiles) may change more rapidly but most (e.g., buildings and industrial plants) have a long lifetime. Thus, the impact of R&D on the system will generally be quite gradual because advanced technology, which is the product of R&D, will penetrate slowly.

Partially for this reason, we have chosen a 50-year outlook for the study. This relatively long horizon is appropriate also because decisions about nearer-term R&D may benefit from a longer-term view of the energy future.

1.2 APPROACH

We looked for answers to "What could make a difference?" from two perspectives. These are represented schematically in Fig. 1.3. One perspec-

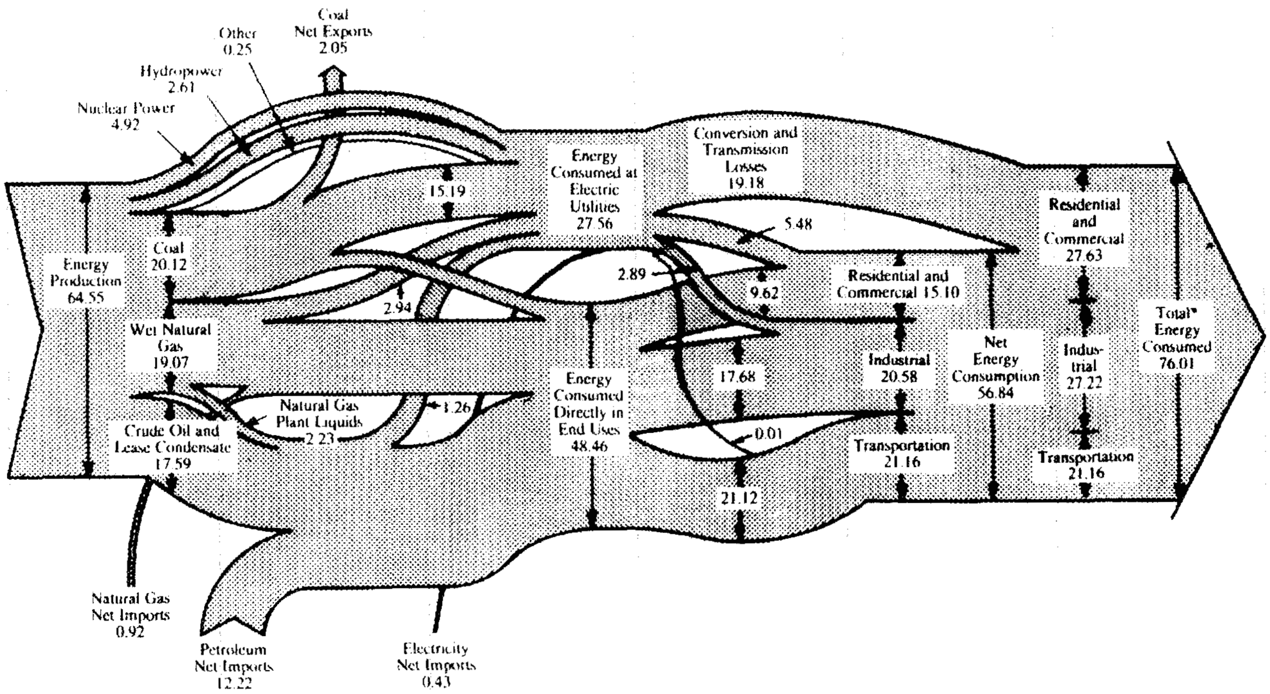

Fig. 1.1. **Flow of energy in U.S. society in 1987; net primary resource use 76 quads.** *Source: Annual Review of Energy 1987*, DOE/EIA-0384(87), U.S. Department of Energy, Energy Information Administration, Office of Energy Markets and End Use, May 1988.

tive is a "top-down" view in which we examined the energy situation, the problems with the energy system, possible future circumstances, and desirable characteristics of the energy systems as a whole. This view served to identify technological needs that can be equated with societal and market demand pull.

In our search for the problems and opportunities that require or provide incentives for new or improved technologies, we carried out a broad review of the literature and consulted with people knowledgeable about energy. Our objective was to gain a comprehensive picture of existing problems and opportunities and some insight into possible future ones. Chapter 2 represents the product of our effort to understand and define the needs of the energy system.

The other perspective represented in Fig. 1.3 is a "bottom-up" view of energy R&D technology. The information base for this view is compiled in Vol. 2, and most of the effort of the ORNL staff on the study was devoted to this aspect. The orientation was on the technology itself; it was a technology-push viewpoint.

We tried to look comprehensively across the energy system from the various sources to end uses. The objective was to identify significant advances and the opportunities and needs for additional R&D. An outline of the technologies and technology areas reviewed is given in Appendix A.

We also looked at various crosscutting areas of science and technology, because advances in these can significantly affect the progress of energy technologies. These crosscutting areas (outlined in Appendix B) include materials science, microelectronics and computing, biotechnology, combustion science, geosciences, effluent management, separation science and decision-making techniques.

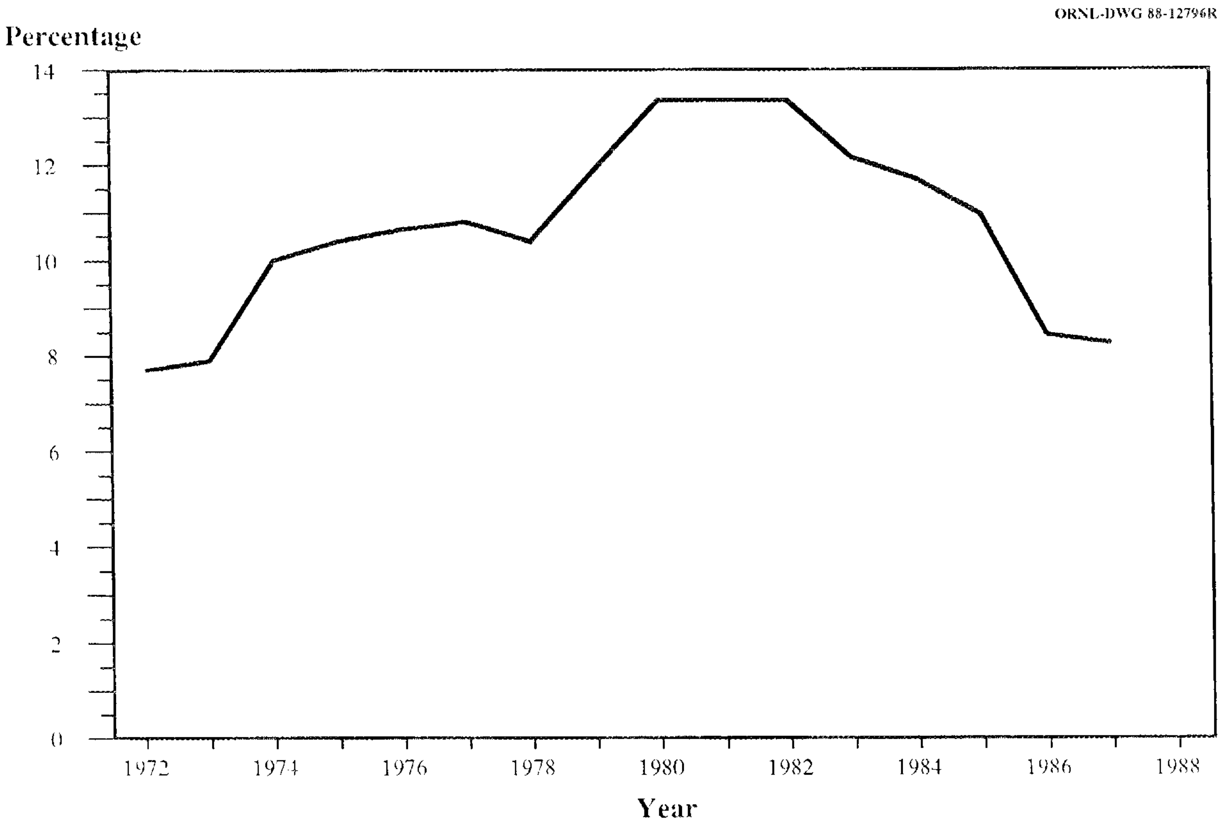

Fig. 1.2. Energy expenditures as a percentage of Gross National Product. *Sources:* Data for 1972-81 taken from Alex Korny, *Dollar Measures of Energy Production and Consumption in the United States 1972-82,* BEA Working Paper 5, BEA87WP-5, U.S. Department of Commerce, 1987; data for 1982-87 calculated from energy expenditures given in *State Energy Price and Expenditure Report*, DOE/EIA-0376(85), October 1987, and from data in *Monthly Energy Review*, DOE/EIA-0035(88/2), February 1988, with GNP data from the *Survey of Current Business*, U.S. Department of Commerce, various issues.

In preparing the reviews that appear in Vol. 2, contributors were asked to review current work in their areas of assignment, both in the United States and around the world. Their R&D reviews relied heavily on research activities of the U.S. Department of Energy (DOE), of course, as well as on those of other organizations such as the Electric Power Research Institute (EPRI) and the Gas Research Institute (GRI).

The R&D options identified by our review were then evaluated to determine their potential contribution to solving energy system problems or their beneficial impacts on the system. As described in Chap. 3, the evaluation used 16 criteria in 6 areas. The 6 evaluation areas were energy significance; economics and international competitiveness; environmental, health, and safety impacts; energy security; social impacts; and less-developed country impacts. The analysis was qualitative and resulted in identification of 50 promising R&D options or foci. These promising options, discussed in Chap. 3, represent our best judgment of the R&D that could make a difference.

To check the potential contribution of the 50 R&D options, we looked at the nation's likely needs from the top down. This evaluation is summarized

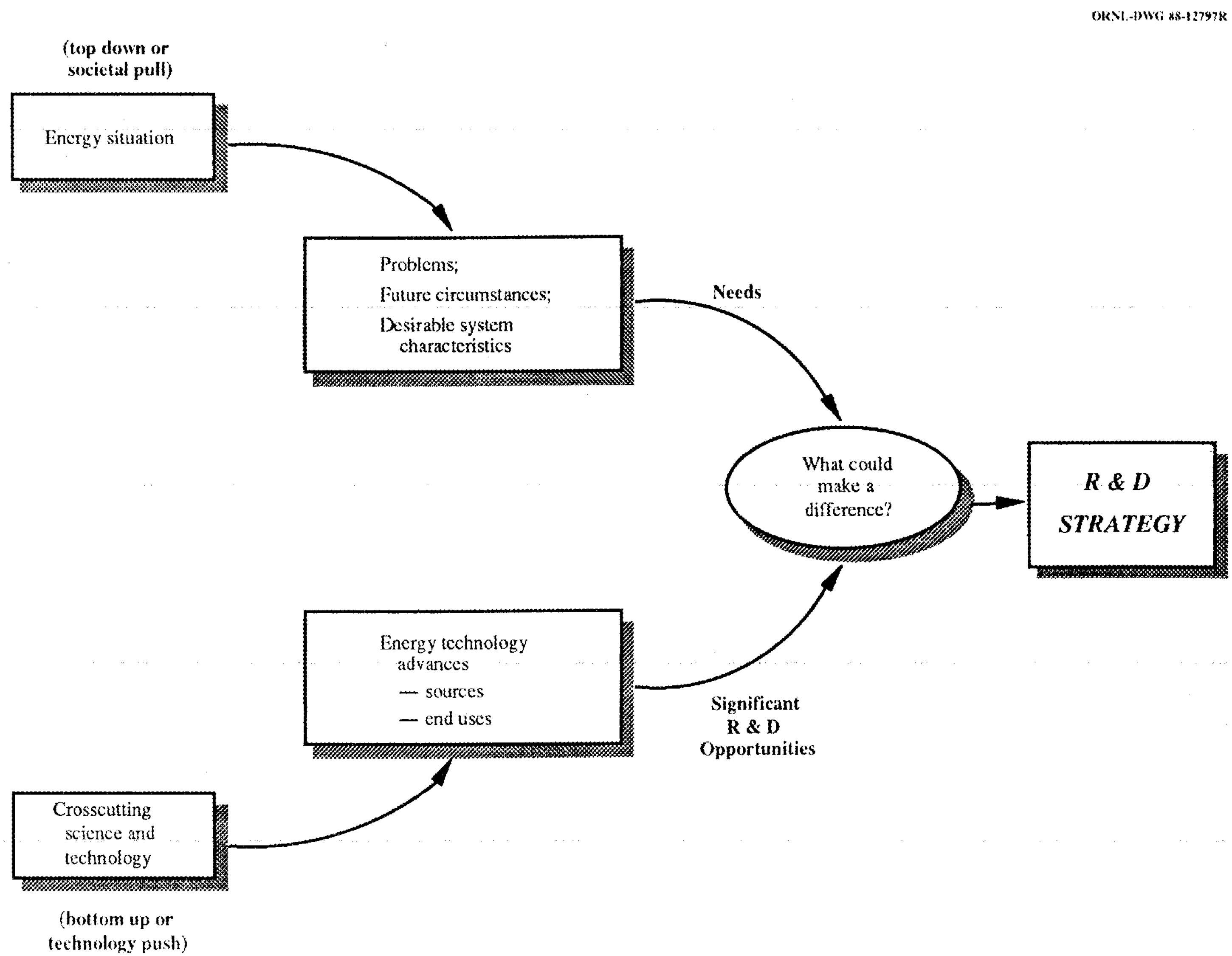

Fig. 1.3. Top-down and bottom-up approaches to analysis used in the study.

in Chap. 4. In sum, we sought to define a balanced strategy given a range of possible future energy needs. We began by asking "What do we want our national energy technology R&D strategy to accomplish?" We reasoned that in addition to providing better technologies R&D should also accomplish three broad system objectives: (1) help solve problems with the system; (2) provide alternatives for coping with or taking advantage of future circumstances, favorable or adverse; and (3) provide new opportunities.

In pursuit of this balanced strategy, we postulated three future energy circumstances. These derived from consideration of two dominant uncertainties: (1) What will be the future level of energy demand, and (2) will fossil fuel use be curtailed because of concern about the greenhouse effect?

Given these uncertainties, we then examined how well our promising R&D options (identified in Chap. 3) address future energy system problems and issues and provide a robust set of alternatives for the three future circumstances. In sum, Chap. 4 assesses whether the 50 options represent a balanced strategy.

It was one thing to embark on this quixotic mission and quite another to accomplish it. If we fell short, the weaknesses and biases manifested by the study should be recognized. For example, although we tried to make the assessment comprehensive and nonparochial, that proved to be impossible. ORNL is not working on all technologies; therefore, our knowledge of some of these was less complete. We sought to compensate by encouraging our participants to communicate with researchers around the country, and sections of the report were sent to colleagues outside ORNL for review. The complete draft of this synthesis report was reviewed both internally and by several colleagues outside ORNL. In addition to the technical literature, we reviewed the multiyear plans of DOE, EPRI, and GRI. Despite these efforts, some R&D areas were not fully assessed, either because of lack of time and human resources or because, in the judgment of the authors, the particular technology was thought to have low probability of making a significant difference.

Our approach to the analysis is qualitative and judgmental. Quantitatively assessing the benefits of future technologies is not possible, in our opinion; the uncertainties are just too great. We did try to explain the bases for our judgments about the advantages and disadvantages of technologies and the needs and opportunities for R&D. Undoubtedly, others may judge the prospects for some technology R&D differently, but perhaps our efforts may serve to stimulate needed debate about critical choices faced by the nation and, in the broader context, the world community of nations.

1.3 ORGANIZATION OF THE REPORT

The following chapters in this report each address a major question. Together, the questions represent those which must be answered to know "What could make a difference?" Chapter 2 responds to "What is the present condition of the U.S. and world energy system?" and serves as the foundation for the study by summarizing the nation's energy problems and opportunities. In providing an overview, the chapter sketches (1) the recent history of energy by comparing what has happened over the past 15 years with what was occurring before the 1973 oil boycott, (2) the current energy supply and demand situation, and (3) a range of expert views of the world's energy future. In summarizing existing and expected problems and opportunities, the chapter provides reference points for judging the desirability of individual R&D options—specifically, R&D which has the likelihood of contributing to the solution of problems or to the creation of attractive new energy technologies. In Chap. 2, we have also sought to achieve an ancillary purpose: to provide a primer for those who are interested in energy R&D but who have not studied it in depth and to offer a refresher for those who may have a familiarity with energy R&D but who have not followed it in recent years.

Chapter 3 asks, "What are the attractive R&D options, judged by their ability to contribute to desirable goals and their likelihood of being technically (commercially) available?" This chapter lists and characterizes some 50 R&D options that we have judged to be particularly attractive when viewed in the context of 16 desirable energy system characteristics. These options are discussed in the commonly used energy resource or technology categories.

Chapter 4 asks, "Does the slate of energy R&D options identified in Chap. 3 represent a balanced

R&D strategy?" The concept of a balanced strategy is defined, and the slate of R&D options discussed in Chap. 3 is then compared with the needs of a balanced strategy. It is shown that in spite of major uncertainties about future energy demands and supply constraints, the set of energy R&D activities likely to be most fruitful under different circumstances will not differ as much in kind as in emphasis and intensity.

Chapter 5 answers "What of a more general nature did we learn or conclude in carrying out this study?" In it we summarize the principal conclusions and make a number of general observations.

Chapter 2
The Energy System in 1988

Several chronic issues affect the energy system of the United States. These include (1) a variety of environmental, health, and safety problems; (2) energy insecurity, especially with respect to petroleum and petroleum products and the instability of oil prices; (3) lack of confidence in nuclear power; and (4) the need of less-developed nations for an increasing share of the petroleum supply. Of course, these issues are not peculiar to the United States; they are felt to one degree or another by most of the industrialized nations of the world.

In this chapter, we examine these problems in the context of history. How did the present circumstances arise? What has been the reaction, particularly with respect to technology change? What may future circumstances be? Will we be able to maintain a stable future? What part can R&D play? We hope to give the reader a sense of where we are, how we got here, and what the uncertainties and options are for the future.

2.1. THE WORLD BEFORE 1973

Since our prospective time frame is 50 years, it might be instructive to look back 50 years as well. In 1937, the energy system was qualitatively not very different from what it is today. Our nation used much less energy, to be sure—about one-fourth as much as in 1987—but we were driving cars, flying airplanes, and refrigerating our food with electricity and gas. We were not yet enjoying air conditioning on a large scale. Coal was king, but oil was rising fast, and electricity was on the way to becoming universally available (with the Tennessee Valley Authority and the Rural Electrification Administration). Then, as now, fossil fuels supplied nearly all commercial energy, and about the same amount of wood fuel was used then as now. Essentially all energy sources were indigenous. Pollution was bad, but much less fuel was being burned; even less coal was used (Table 2.1). One difference was that nuclear power had not been invented, but we were using wind power. In 1937, energy was not a national issue, but electrification was.

Over the next several decades, coal lost market share to oil, gas, and hydropower. World War II was followed by 25 years of general economic growth, and although energy use rose by a factor of four, energy supply was not a problem. Total energy use rose roughly in proportion with the Gross National Product (GNP), and electricity and gas rose more rapidly. To fuel this economic growth, we began to import cheap oil from the Middle East as domestic sources became more expensive. By 1957, net imports had risen to 12% of total petroleum use; by 1967, to 19%; and by 1973, to 37%. This glut of cheap oil was developed and controlled by a group of U.S. and Western European oil companies, the so-called seven sisters. They played the same role internationally as the Texas Railroad Commission did domestically. They stabilized oil supply and oil prices.

The cost of oil and gas was so low that our cars got bigger, we neglected to insulate our homes, and our industries failed to improve their energy productivity as they had in previous decades. Also, in the 1960s, nuclear power became commercial with the hope of providing inexhaustible power at low cost.

Something else happened in the 1960s: an upsurge of environmental awareness that became and has remained a crucial force in the energy system and in energy technology development and deployment. For example, in the late 1960s and early 1970s, a shift from coal to oil and gas for electricity generation was encouraged, a trend reversed after the Arab oil embargo but one that is apparent again today. Also, the earnest questioning of nuclear power began in the early 1970s and was the cause of the Calvert Cliffs decision in 1971 requiring the Atomic Energy Commission to conform to the National Environmental Policy Act in licensing nuclear power plants. The questioning has grown steadily to this day.

Table 2.1. U.S. and world primary energy use and associated CO_2 emissions[a]

	Oil														CO_2 emissions		
	% imports	Total oil		Gas		Coal		Fossil		Hydro-electric		Nuclear		Total primary	$(10^{15}$ g C/yr)	E/GNP [10^3 Btu/(1982)$]	E/capita (10^6 Btu/person)
		q	%	q	%	q	%	q	%	q	%	q	%	q			
1937																	
U.S.		7	33	2	11	12	55	21	99	0	1			21	0.4	29.8	161
World		12	20	3	5	45	75	60	99	0	1			60	1.2		29
1947																	
U.S.		12	36	4	13	16	50	32	99	0	1			32	0.7	29.9	221
World		18	24	6	9	48	66	72	99	0	1			72	1.4		32
1957																	
U.S.	12	18	44	10	25	11	27	39	96	2	4			40	0.8	26.1	236
World		35	33	12	11	53	50	100	94	6	6			106	2.2		37
1967																	
U.S.	18	25	44	18	31	12	21	55	96	2	4			58	1.0	25.3	290
World		70	40	30	17	65	37	165	94	11	6			176	3.3		51
1973																	
U.S.	37	35	47	23	30	13	17	70	95	3	4	1	1	74	1.3	27.1	351
World		111	47	42	18	66	28	220	94	13	6	2	1	235	4.5		60
1977																	
U.S.	49	37	49	20	26	14	18	71	93	3	3	3	4	76	1.3	25.8	346
World		118	46	46	18	73	28	237	92	15	6	5	2	258	4.8		61
1985																	
U.S.	29	31	42	18	24	17	24	66	90	3	5	4	6	74	1.3	20.7	309
World		112	38	59	20	90	31	260	88	20	7	14	5	295	5.3		61
1986																	
U.S.	36	32	43	17	23	17	23	66	89	3	5	4	6	74	1.3	20.0	308
World		115	38	59	20	92	31	266	88	21	7	15	5	302	5.4		61
1987																	
U.S.	37	33	43	17	23	18	24	68	89	3	4	5	6	76	1.3	19.9	312
World		117	38	62	20	95	31	273	88	21	7	16	5	310	5.5		62

[a]Note: Total primary energy in this table does not include biomass. Energy from biomass is estimated to be 2 to 3 quads/year in the United States and probably ten to twenty times as much worldwide. Columns headed by "q" represent the energy supplied by each source in quads.

Sources:

Energy: U.S.

1973-1987:	U.S. Department of Energy, Energy Information Administration, *Monthly Energy Review*, Feb. 1988, DOE/EIA-0035(88/02), p. 7.
1957, 1967:	U.S. Department of Energy, Energy Information Administration, *Annual Energy Review 1986*, DOE/EIA-0384(86), 1987.
1937, 1947:	Putnam, Palmer C., *Energy in the Future*, New York: D. Van Nostrand, 1953, pp. 374, 379.

Energy: World

1967-1987:	British Petroleum Company, *BP Statistical Review of World Energy*, various editions, including June 1988. (Given in metric tonnes of oil equivalent and converted to quads at 10^4 calories/gram = $39.685 * 10^6$ Btu/tonne (metric tonne of oil equivalent), as defined by BP.
1957:	United Nations, "World Energy Supplies, 1950-1974," UN Statistical Papers, Series J, No. 19, 1976, p. 3.
1937, 1947:	Putnam, Palmer C., *Energy in the Future*, New York: D. Van Nostrand, 1953, pp. 441-42.

CO_2 emissions: World

1937-1982:	U.S. Department of Energy, *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, DOE/ER-0239, December 1985, pp. 69-70.
1985-1987:	Computed from oil, gas, coal energy consumption using coefficients derived from DOE/ER-0239.

CO_2 emissions: U.S.

1937-1987:	Computed from oil, gas and coal consumption using coefficients 17.4 grams carbon/MJ for oil, 13.7 g C/MJ for gas, 23.9 g C/MJ for coal (18.35, 14.45, 25.21 g/10^3 Btu respectively), taken from R. M. Rotty and G. Marland, "Constraints on Fossil Fuel Use," pp. 191-212 in W. Bach, J. Pankrath, and J. Williams, Eds. *Interactions of Energy and Climate*, Boston: D. Reidel Publishing Co., 1980.

Gross National Product: U.S.

1937-1985:	U.S. Department of Commerce, *Survey of Current Business* **66**(2), 20, Feb. 1986.
1986, 1987:	*Survey of Current Business* **68**(4), 10, April 1988.

Population: U.S.

U.S. Bureau of the Census, *Historical Statistics of the United States*, 1970; *Statistical Abstract of the United States*, 1987.

World

1937, 1947:	Putnam, op. cit.
1957-1987:	United Nations, *World Population Prospects*, Population Studies No. 98, p. 48, New York, United Nations, 1986.

Then came the Yom Kippur War and the Arab oil embargo of December 1973, and suddenly energy was a prominent national issue. The system, stable for so many decades, was suddenly very unstable.

2.2. THE WORLD AFTER 1973

By 1973, oil was supplying half our total energy requirements, and our net imports were 37% of petroleum use (Table 2.1). Although the Arab oil embargo did not actually result in any huge physical curtailment of U.S. supply, it was certainly sufficient to cause the world price of oil to triple in a few months. The U.S. consumer did not immediately see a price rise of this magnitude because of price controls, but the embargo resulted in gasoline shortages, lines at filling stations, and an economic recession.

The embargo triggered a great flurry of actions by the government and other institutions, as well as by individuals. Many laws were passed that changed the rules of the energy system management. Among these actions was the institutionalization of a national energy R&D establishment. It included the Electric Power Research Institute (EPRI), formed in 1973 to stimulate R&D on the electricity system. The Energy Research and Development Administration (ERDA was formed in 1974 to consolidate the energy-related R&D activities of the government, and was in turn subsumed into the Department of Energy (DOE) in 1977. Also, in 1974 the Solar Energy Research Institute was founded and became one of the DOE laboratories. The Gas Research Institute (GRI) was organized in 1978 to do for gas what EPRI did for electricity. No such umbrella R&D organization has been established for petroleum, although it has often been suggested and is still an active topic. The fact that it has not materialized is testimony to the strength and tradition of R&D in the oil industry. Since the formation of this national R&D establishment, virtually all aspects of energy technology have become the subject of R&D to some degree.

Just as the first oil price shock in 1973-74 was unexpected, so too was the second, which was triggered in 1979 by the Iranian revolution. The word "triggered" is probably appropriate because the sudden price change was not transient but remained high for several years after the shift. This time oil prices doubled, causing an inflationary recession. Also, prices were passed along more rapidly to the U.S. consumer because oil price deregulation was well under way. In Fig. 2.1, the recent price shocks are put in the perspective of historical trends since 1860. Although oil prices have fluctuated a good deal in the past, the price increases of the 1970s were by far the largest in modern times.

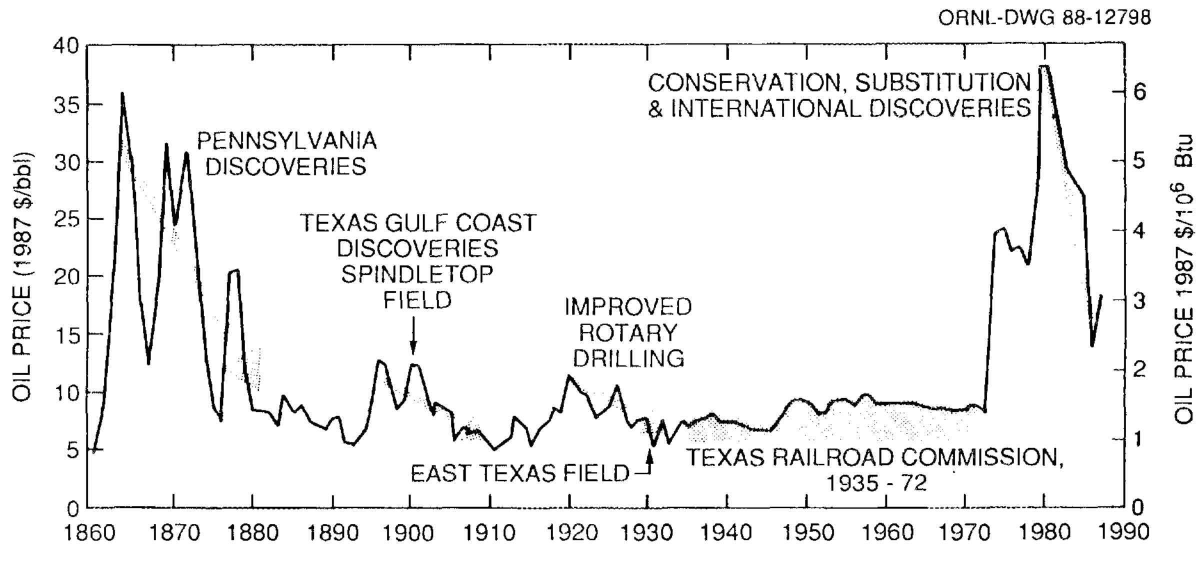

Fig. 2.1. **Historical trends in oil prices (constant 1987 dollars per barrel).** *Source:* API, DOC, and WAC estimates. Redrawn with permission from A. E. Sieminski, "Future of Oil: Supply and Price Trends," County NatWest/Washington Analysis Corporation, paper presented at 1988 Energy Technology Conference, Washington, D.C., Feb. 18, 1988.

The economic response to these two oil price shocks was classic: demand for oil moderated, as did the demand for energy sources in general (Fig. 2.2), and supply increased. But the magnitude of the moderation was unexpectedly vigorous. In the mid 1970s, few people expected that the U.S. would be using the same quantity of primary energy in 1986 as it did in 1973, and about 8% less oil; yet during the same period, the GNP rose 35% in constant dollar terms, and the population increased by 13%. The same general behavior was exhibited by other industrialized nations, as indicated by Figs. 2.3 and 2.4. Figure 2.3 shows a plot of annual energy use divided by GNP for total energy, oil, and electricity, all normalized to the values in 1973. Total primary energy/GNP (E/GNP) for the United States decreased 27% between 1973 and 1987. Figure 2.4 shows that the Organization for Economic Cooperation and Development (OECD) countries* combinedwould have used 26% (41 quads) more primary energy in 1987 if the ratio of energy use to GNP had remained the same as it was in 1973. The OECD countries used 9% less oil in 1987 than in 1973, although demand has risen 4.4% since 1985.

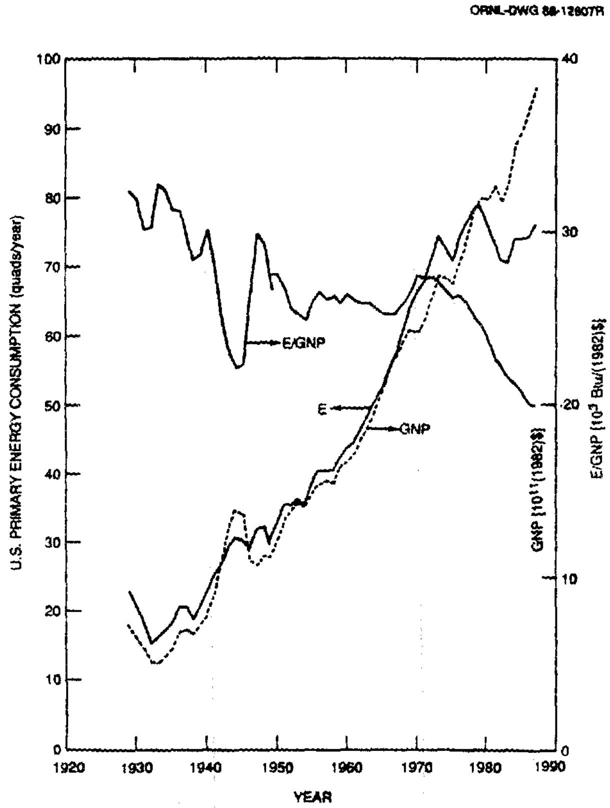

Fig. 2.2. Total primary energy consumption in the United States (1929-1987) and the ratio of energy use (E) to Gross National Product (GNP). *Sources*: GNP: U.S. Department of Commerce, *Survey of Current Business*, Feb. 1986, April 1988 (see Table 2.1). E: DOE/EIA, *State Energy Data Report*, 1960-86, DOE/EIA-021(86), p. 21. DOE/EIA *Monthly Energy Review*, DOE-EIA-0035 (88/2), p. 7.

For the rest of the world, the demand for energy has been qualitatively similar in some respects but different in others. Oil use for the rest of the world rose by 50% from 1973 to 1987, but about two-thirds of that increase occurred between 1973 and 1979. Total energy use by non-OECD countries rose 73%. Per-capita energy use also rose for non-OECD countries, as indicated in Fig. 2.5. As a result, total world primary energy use rose 32% between 1973 and 1987.

Just as demand for energy in general and for oil in particular diminished in response to the oil price shocks, supplies also changed dramatically. World oil production capacity increased by some 16%, as indicated in Fig. 2.6, despite the loss of about 5 million bbl/day (10 quads) caused by the Iran-Iraq conflict. The increase in capacity was the result of heroic efforts everywhere, including such unlikely spots as the North Sea and Alaska. In addition, gas, coal, hydroelectric power, and nuclear power all increased dramatically both in absolute terms and in market shares, as shown in Table 2.1, shifting the burden from oil.

The net result of all these supply-demand adjustments was that the gap between worldwide demand for oil and world production capacity widened, beginning in 1979, as shown in Fig. 2.6. From 1981 to 1985, the constant dollar price of oil declined steadily, as shown in Fig. 2.1. Then in January 1986, oil prices crashed by one-half with Saudi Arabia's decision not to support a price of $28/bbl. As with the price rises, this sudden drop was generally unexpected.

It is a reasonable contention that the large gap between production capacity and oil consumption ultimately led to the collapse of oil prices in January

*The OECD comprises the following nations: Austria, Belgium, Denmark, Finland, France, Greece, Iceland, Republic of Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, and West Germany; Canada and the United States; Australia and New Zealand; Japan.

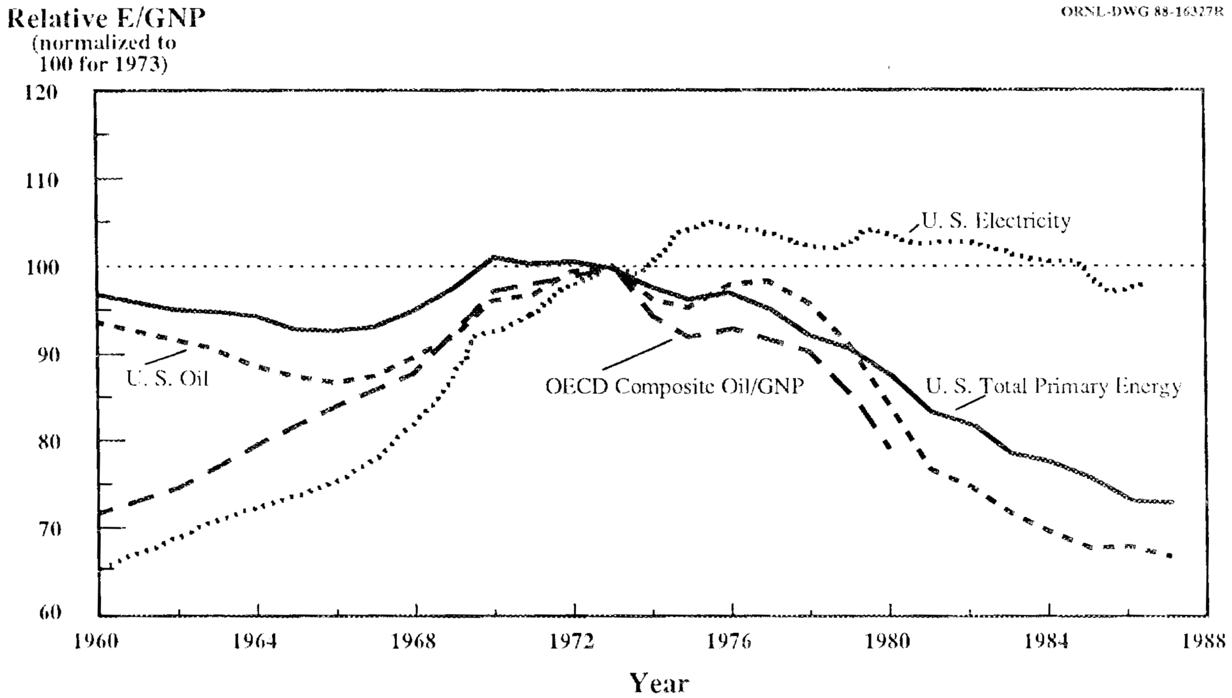

Fig. 2.3. Apparent efficiency of energy use continues to increase. *Sources:* U.S. total E/GNP: same as Fig. 2.2; Electricity: 1960-1976: *EEI Statistical Yearbook*, 1976. 1973-1987: *Monthly Energy Review*, Op Cit. Oil: same as E. OECD: International Energy Agency, *World Energy Outlook,* OECD, 1982.

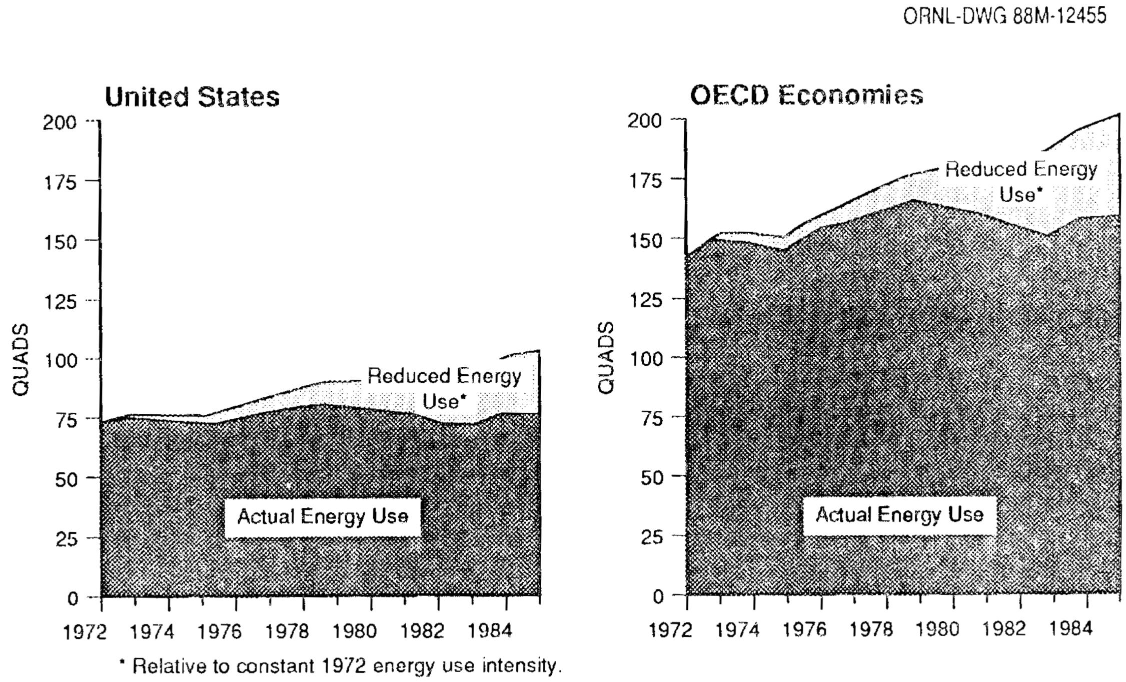

Fig. 2.4. Efficiency gains have moderated growth in energy demand. *Sources:* DOE, *Energy Use Trends in the United States 1972-1984*; EIA *Monthly Energy Review* July 1986; DOE Policy, Planning, and Analysis, Office of Oil and Gas Policy; DOE, *Patterns of U.S. Energy Demand* DOE/PE-0076, August 1987.

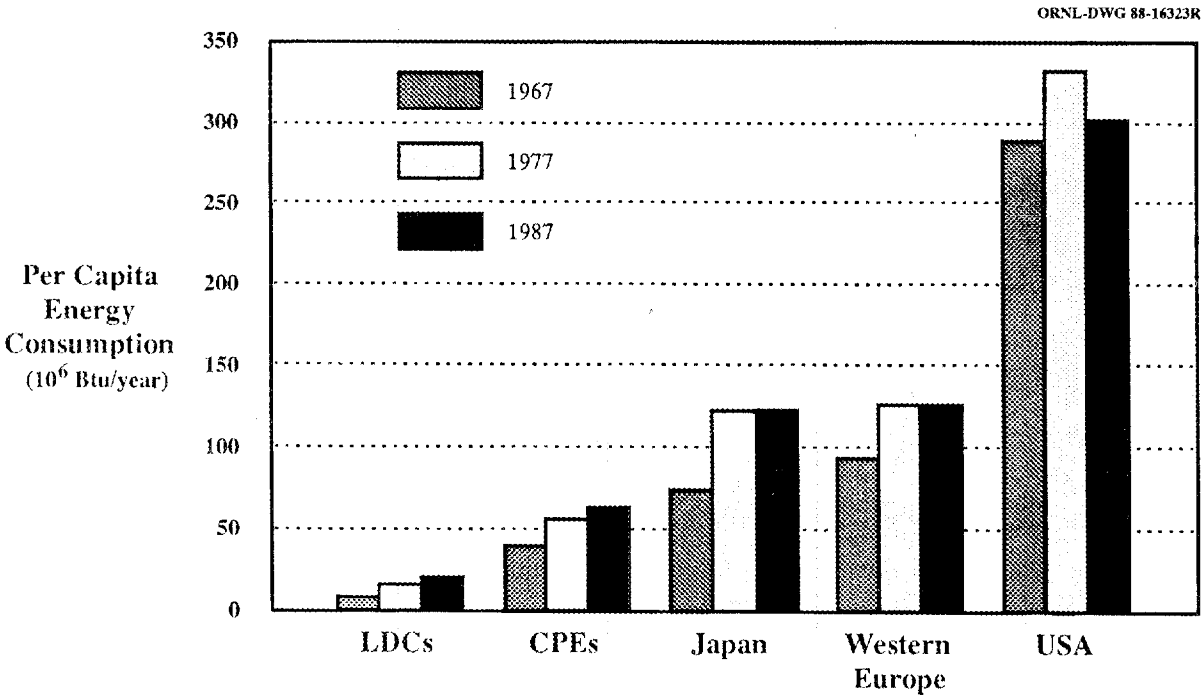

Fig. 2.5. Primary energy consumption per capita. *Source:* Redrawn with permission from *B. P. Statistical Review of World Energy*, British Petroleum Company, June, 1988.

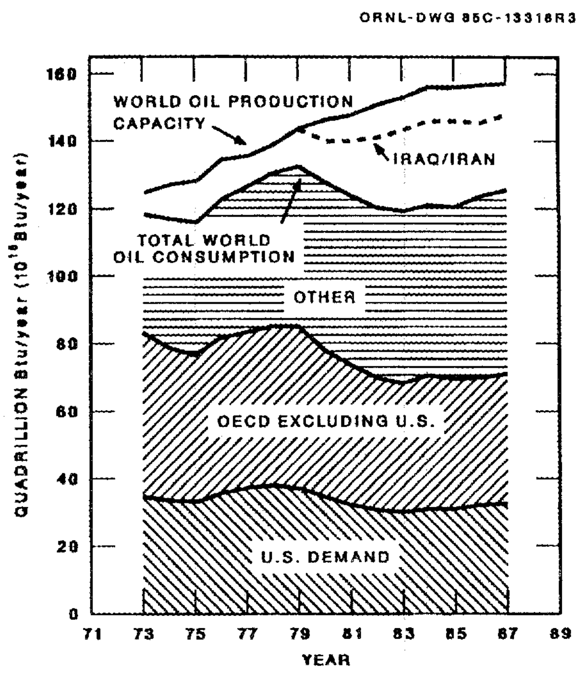

Fig. 2.6. World oil consumption and world oil production capacity. *Sources:* British Petroleum Company 1988; U.S. Central Intelligence Agency, *International Energy Statistical Review*, various issues.

1986. In fact, the Energy Information Administration (EIA) has proposed a correlation between yearly changes in oil prices and the percentage of the oil production capacity of the Organization of Petroleum Exporting Countries (OPEC) that is actually used (EIA 1985). A plot similar to the one used by EIA is shown in Fig. 2.7. The dashed line suggests that world oil prices do not change much when OPEC production is between 70 and 80% of capacity. When production exceeds 85% of capacity, prices rise precipitously, and when production falls below 60 to 70% of capacity, prices drop.

During this trauma with oil markets and energy system changes and adjustments, the United States did not falter in its commitment to improve the environment. During the 15 years since 1973, environmental legislation continued to be enacted at a furious rate, including toughened restrictions on air emissions that affected highway vehicles and stationary power sources just when the emphasis was to improve the efficiency of the former and to switch the latter to coal. Other legislation involved the handling of toxic and hazardous substances, including nuclear wastes. In addition, the Three-Mile Island accident in 1979 resulted in the reevaluation

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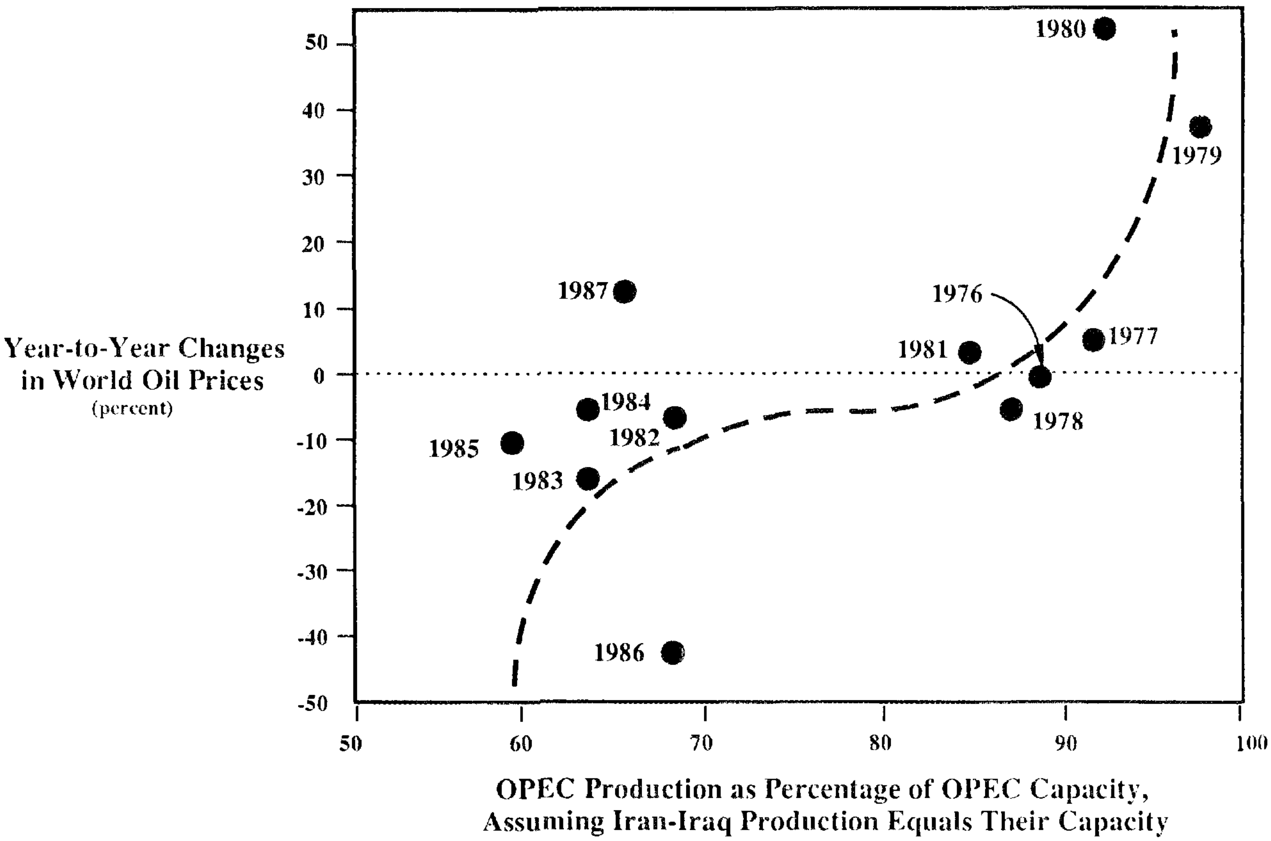


Fig. 2.7. **Change in world oil prices versus utilization of OPEC production capacity.** *Source:* adapted from EIA 1985.

of the safety of every nuclear plant existing or under construction and the redesign or retrofitting of most.

All of these substantial changes in the system were not without their costs. Both of the oil price increases led to or exacerbated recessions and were factors in painful industrial dislocations and the decline of energy-intensive heavy manufacturing. The latter was caused in no small measure by stiff competition from abroad. It is fair to say that energy prices experienced by U.S. industries during this period were no higher (and often lower) than those experienced by our foreign competitors, but high interest rates made needed capital improvements costly. These high rates, in combination with rising energy costs, environmental restrictions, and competition, contributed to the enormous dislocations in U.S. industry from which the country has yet to fully recover. In macroeconomic terms, the growth of the U.S. economy, which had averaged 3.6%/year between 1950 and 1973, slowed to 2.4%/year between 1973 and 1987.

Thus, the oil price shocks of the 1970s were perhaps the most visible of a series of external shocks to the U.S. economy. A popular belief in the 1970s was that the U.S. economy would remain dominant in the world regardless of developments elsewhere. Still, retrospective analysis indicates that the economic situation was changing even before the oil price shocks. For example, the growth rate of labor productivity in America fell from 2.0%/year (1960-68) to 1.5%/year (1968-73), 1.0%/year (1973-78), and 0.6%/year (1978-85). Although no clear consensus exists about the reasons for this decline (Wolff 1985), there is agreement that significant changes in the rate of productivity growth have occurred over the past two decades.

The supply shocks of the 1970s were particularly suitable to a supply-push inflationary adjustment; and indeed that is what happened. In each of the oil price shocks, U.S. labor became less productive in real terms. In Fig. 2.8, a simple estimate of the impact of the oil shocks is illustrated in terms of

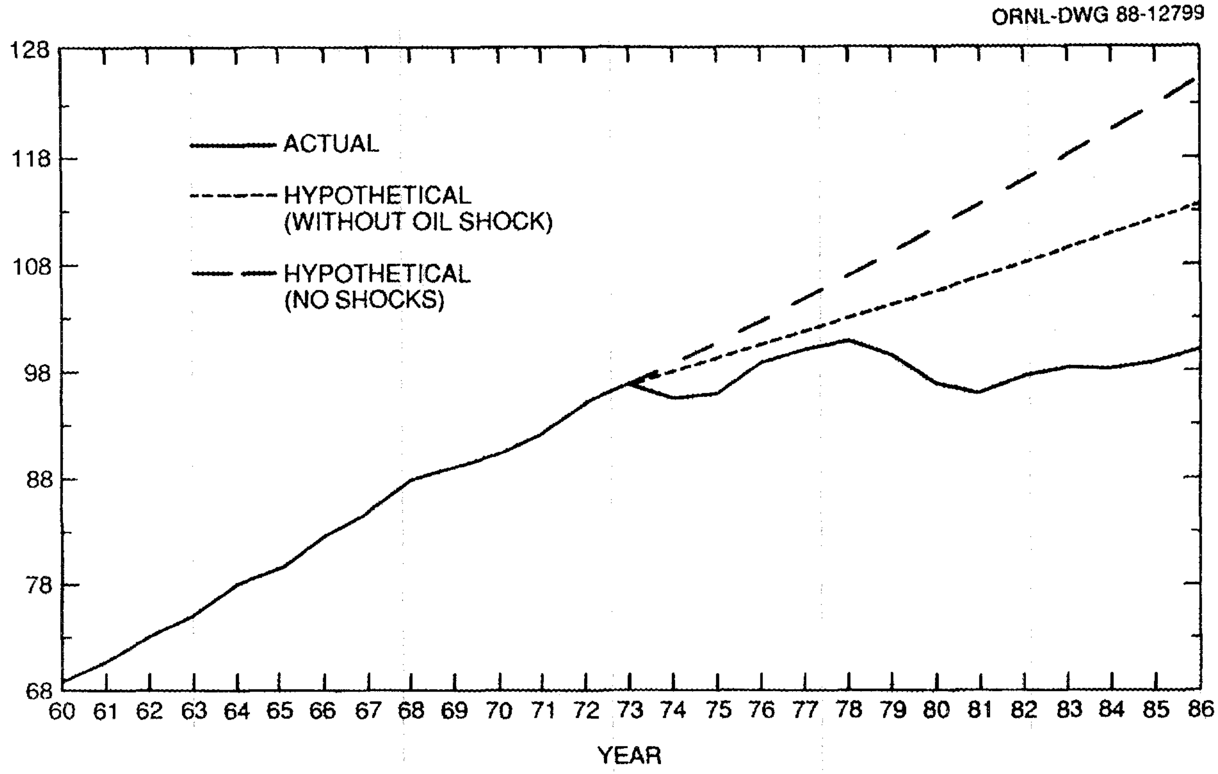


Fig. 2.8. Effect of oil price shocks on real compensation per hour in the U.S. business sector. Hourly compensation is indexed to 1977 value as 100. *Source:* Council of Economic Advisors, Economic Report of the President, 1987, Table B43, p. 294.

average real compensation in the business sector. The line labeled "Hypothetical (no shocks)" extrapolates from 1973 by using the 1968-73 trend in real wages. This line indicates the level that real wages would have reached if there were no post-1973 declines in the trend. The line labeled "Hypothetical (without oil shocks)" extrapolates from 1973 using the post-1973 average trend in real wages. This extrapolation takes into account that other conditions were changing, lowering American labor productivity. Comparing this line with the actual trend line suggests that the typical American worker is now significantly poorer as a result of the oil-price shocks.

In summary, the U.S. and world energy systems have responded to the oil price shocks by very significant adjustments and fuel switching on the source side of the equation and by very substantial increases in the efficiency of energy use on the demand side. These efficiency improvements have been largest in OECD countries. The systems remain dominated by fossil fuels just as they were 50 years ago, but today oil instead of coal is the principal fuel type. However, since the Arab oil embargo, oil consumption has risen and fallen back to below 1973 levels, whereas coal has experienced significant growth, as have gas, hydropower, and nuclear power. Over the past 15 years, the worldwide growth of nonfossil fuels has been much faster than fossil: 3%/year for hydropower and 15%/year for nuclear power, compared with only 1.5%/year for fossil fuels of all types.

Thus, although much about the energy systems of the world and the United States remains qualitatively the same as before the Arab oil embargo, and although the systems are ponderous with much inertia, they have changed and are continuing to evolve slowly. Are the systems as stable as they were before the embargo? We return to this question in Sect. 2.5 when we talk about chronic system problems, but first we review in somewhat more detail what has happened since 1973 in each energy-use sector and with each energy source, highlighting both difficulties and promise.

2.2.1. Energy End Use

In the mid 1970s, few people expected that the United States would use the same quantity of primary energy in 1986 as it did in 1973. The apparent increase in the productivity of energy use by the U.S. economy, as measured by the ratio E/GNP, occurred in all end-use sectors (i.e., buildings, industry, and transportation. This behavior is shown in Table 2.2. For residential buildings, the energy use per household decreased from about 215 million Btu/year in 1973 to about 174 million Btu/year in 1983—a 19% reduction. Annual energy use per square foot in commercial buildings apparently decreased about 7%, although it is difficult to know how much allowance to make for unoccupied space. Obviously, some of these changes were caused by lifestyle changes, such as turning down thermostats, and some were caused by technical improvements, such as installing more insulation, tightening up buildings, or using more efficient equipment for heating, ventilating, air conditioning, and lighting. For residential use, some apparent improvement was also caused by the increased use of wood for heating, which is not accounted for in Table 2.2. From numerous studies, however, it is clear that much of the improvement can be attributed to technical changes.

Similar improvements occurred in the industrial sector, where energy use per dollar of output decreased by 30%. Probably a third or more of this improvement resulted from structural changes in the industrial sector (i.e., a shift away from energy-intensive manufacturing, although it appears that heavy manufacturing is making a bit of a comeback today). Nevertheless, one-half to two-thirds of the apparent reduction in energy use per unit of output in the industrial sector has been caused by improvements in energy-use efficiency (DOE 1987a).

In the transportation sector, similar improvements were observed. Energy use per vehicle mile dropped 22% for automobiles and 18% for light trucks. Very little change in energy used per vehicle mile was observed for heavy trucks and buses, although with this measure significant technical improvements are obscured by trends towards heavier trucks and multiple-trailer trucks, as well as by a retreat from the lower highway speeds of the 1970s. The automotive fleet efficiency continues to improve as new cars replace the old. Improvements are caused by smaller, lighter vehicles with less aerodynamic drag and by innovations such as radial tires and microelectronic-controlled fuel injection and ignition. For the scheduled airlines, energy use per passenger mile decreased by 43%. Part of this decrease was the result of increased passenger loading, but significant technical improvements were also made.

It should be noted that no apparent improvement in the efficiency of electricity generation (also shown in Table 2.2) occurred in the United States during this period, partly because the efficiency of the steam Rankine cycle used in modern coal-fired steam plants has not increased in the past several decades and because many plants were derated by the addition of emission control devices.

In addition to efficiency improvements, significant fuel switching occurred. In the buildings sector, the use of petroleum products dropped about 50% for residences and about 28% for commercial buildings between 1973 and 1983. During the same period, overall energy use stayed about constant for residences but grew about 15% in the commercial sector, indicating the significance of the shift away from oil in both of these sectors. Similarly, in electricity generation, petroleum use dropped 63%, from 3.5 quads in 1973 to 1.3 quads in 1987, despite the fact that electricity demand grew 38%. The situation is not nearly as clear for industry. Nevertheless, the industrial sector decreased its use of oil, gas, and coal by almost 7 quads between 1973 and 1983, while increasing its use of electricity by more than 1 quad, including losses in generation and distribution.

It is possible that some productivity improvement in the end use of energy will continue despite lower fuel prices. Even at today's prices, many efficiency improvements are still good investments (Rosenfeld and Hafemeister 1988), and as the capital stock turns over, they will be made. Second, various standards have permeated society, including new building codes, efficiency standards for appliances, and the Corporate Average Fuel Economy (CAFE) standards for new automobiles and light trucks. A great deal has been learned about efficient energy use, and this knowledge has been or is being incorporated into the standards and practices of the engineering and architectural community and into the university curricula of these professions.

Third, new technology is being developed that should continue to fuel the efficiency revolution. Figure 2.9 indicates current estimates by DOE of the potential reduction in energy use if technologies now being developed under DOE programs are com-

Table 2.2. Apparent reductions in energy intensiveness of end-use sectors in the U.S. economy, 1973-1983

	Buildings[a]		Industry	Transportation[a]			
	Residential	Commercial		Automobiles	Light trucks[b]	Air[c]	Electricity
Total energy use (quads)							
1973	14.6	9.5	31.6	9.83	2.10	1.44	19.8
1978	15.6	10.5	31.5	10.21	3.01	1.44	23.6
1983	14.6	10.9	25.7	8.74	3.19	1.44	24.6
Activity level	Number of house-holds	Sq. ft. floor area	Output (indexed to 100 for 1967)	Vehicle miles/ year	Vehicle miles/ year	Passenger miles/ year	Net electricity generation (quads)
1973	68×10^6	41×10^9	127	1.05×10^{12}	177×10^9	162×10^9	6.35
	76×10^6	47×10^9	147	1.15×10^{12}	279×10^9	227×10^9	7.53
1983	84×10^6	51×10^9	147	1.20×10^{12}	328×10^9	282×10^9	7.89
Energy per unit activity	10^6 Btu/ household	10^6 Btu/ sq. ft.	Quad/ output index	Btu/ mile	Btu/ mile	Btu/ passenger mile	Energy input/ electricity generation
1973	215	0.23	0.25	9400	11,900	8900	3.11
1978	205	0.22	0.21	8900	10,800	6300	3.14
1983	174	0.22	0.17	7300	9,700	5100	3.12

[a]Energy use is on a primary energy basis and includes losses in electricity generation, transmission, and distribution.

[b]Reported by Federal Highway Administration as two-axle, four-tire trucks.

[c]Certificated route air carriers; does not include general aviation.

Sources: Energy Information Administration. 1983. *State Energy Data Report*. DOE/EIA-0214(83) and (86). U.S. Department of Transportation. 1985. Federal Highway Administration, Highway Statistics. Davis, S., D. Shonka, and P. Hu. 1988. *1988 Automated Transportation Energy Data Book*. Draft. Oak Ridge National Laboratory, Oak Ridge, Tenn. To be published as Edition 10 of the *Transportation Energy Data Book*.

mercially successful and penetrate the market substantially by 2010 (DOE 1987b). Specifically, it indicates a potential reduction in primary energy requirements of 22% and a reduction in petroleum products of 38%. Other studies of the energy efficiency improvement potential for the United States show similar results (See, for example, the synopsis by Carl and Scheer 1987).

Something else happened during the past 15 years. An energy conservation ethic grew. People felt that saving energy was the right thing to do. Also, they could protect themselves somewhat against the uncertainties of energy prices and often save money; but since the price crash in 1986, this ethic may be waning.

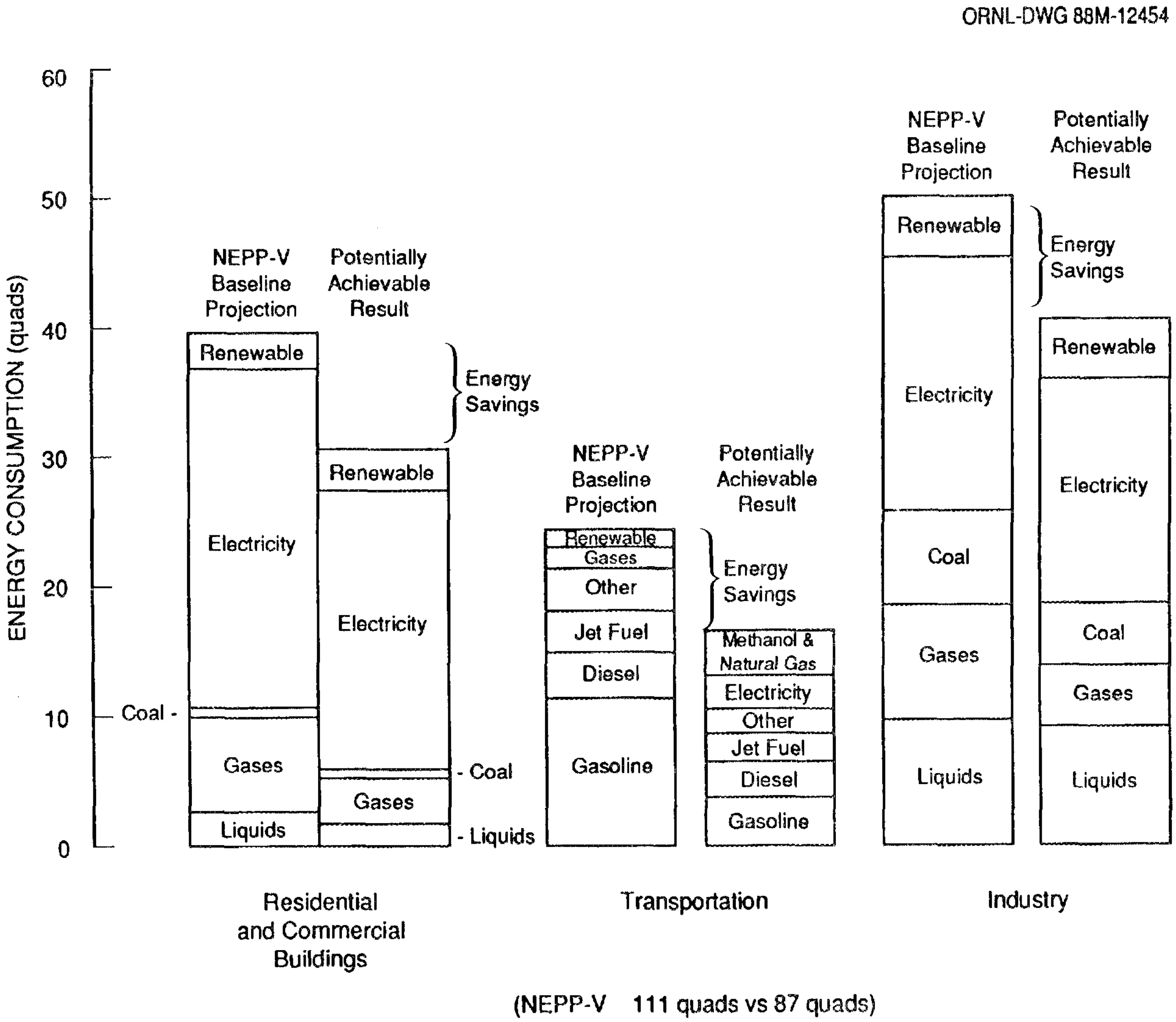


Fig. 2.9. Potential impacts of DOE energy conservation R&D on projected energy use in the year 2010. *Source: 1989 DOE Multiyear Plan for Conservation.*

2.2.2 Energy Sources

Oil

Refined liquid petroleum products are marvelous fuels. They are relatively clean burning, they have very high energy density (energy per unit volume or mass), and they are liquids at room temperature, making them easy to handle, pump, and store. They are wonderfully portable and transportable fuels, and they are easily used at any scale from very large to very small equipment. Consequently, petroleum products supply virtually all of our transportation energy, and two thirds of total petroleum use goes to transportation. Transportation is the critical use that makes us so dependent on petroleum. The other one-third of the uses are more easily substitutable, except in the use of petroleum as a chemical feedstock and for farm equipment.

The problem, of course, is the geopolitics and economics of petroleum because most of the low-cost oil is in the Middle East, an unstable part of the world. Figure 2.10 shows the geographical distribution of the reserves and estimated undiscovered resources of petroleum. At present use rates

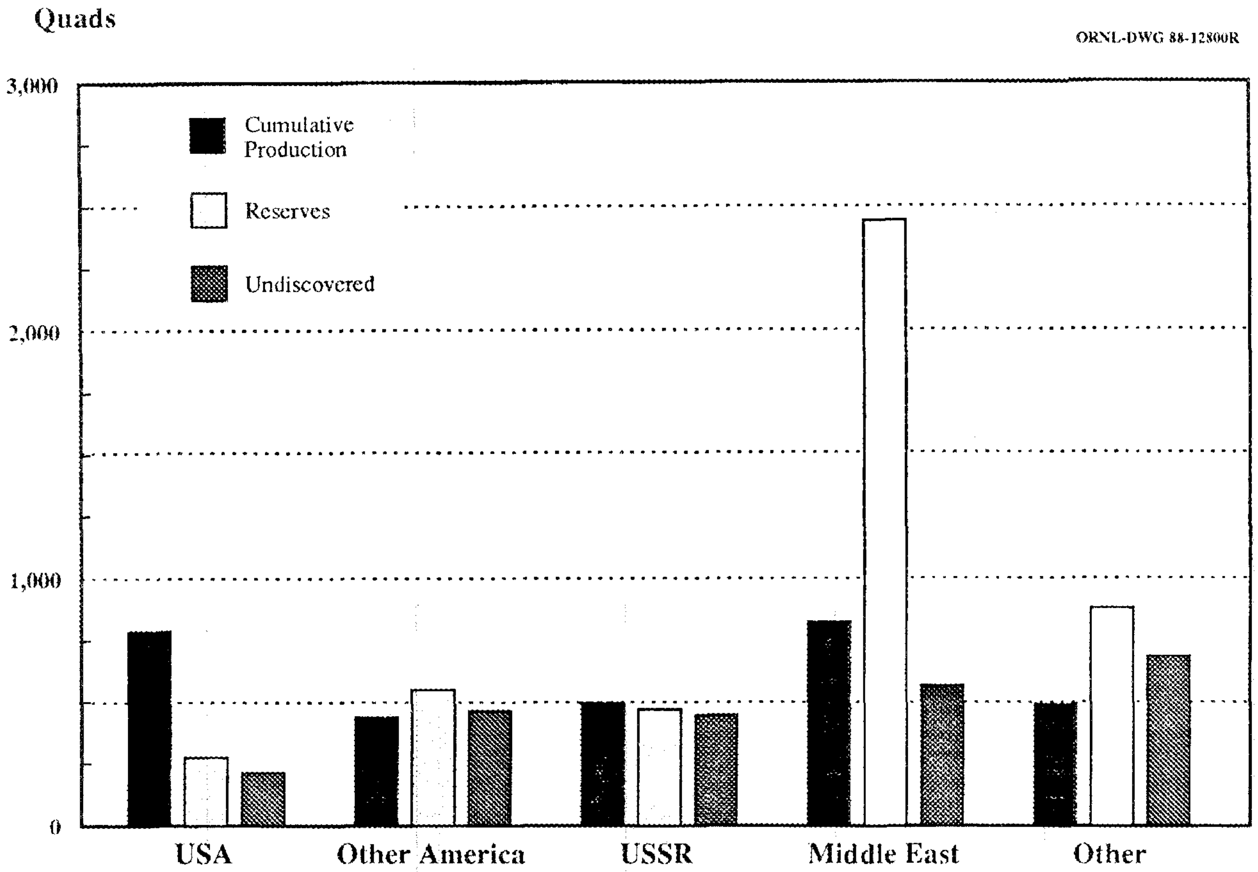


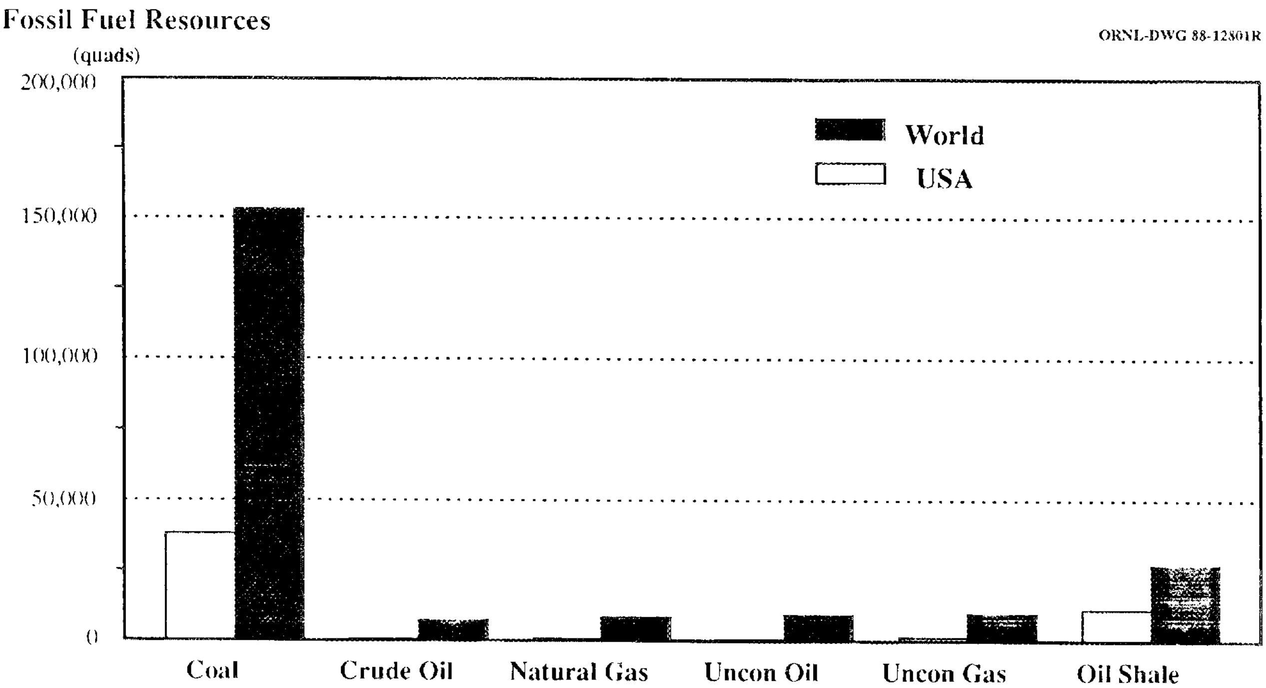
Fig. 2.10. **World oil resources as of Jan. 1, 1985; cumulative production, identified reserves, and undiscovered resources of crude oil by regions.** *Source*: C. D. Masters et al., *World Resources of Crude Oil, Natural Gas, Natural Bitumen and Shale Oil*, Twelfth World Petroleum Congress, Houston, 1987.

these "conventional" petroleum resources are equivalent to about a 60-year supply for the world as a whole, but only about 15 years for the United States, which explains forecasts of increased reliance on foreign sources.

Although conventional and inexpensive petroleum is a limited resource both in quantity and geographically, fossil fuel in general is a very big resource. Figure 2.11 shows the energy content of the various fossil fuels for the United States and the world. Vast quantities of lower-grade fossil fuel exist, notably coal and oil shale. By comparison, resources of oil and gas are relatively very small. At a price, the lower-grade fuels can be upgraded to liquids that can substitute for petroleum products for transportation and other uses.

Since 1973, much has been learned about these conversion technologies, and many variations have been tried. For coal, these include both (1) direct liquefaction by hydrogenation, followed by further processing and refining and (2) indirect liquefaction by gasification, followed by catalytic reforming, as in the Fisher-Tropsch process developed before World War II. It may be argued that the cost of producing liquids from coal or oil shale puts a cap on world oil prices. This cap can be lowered by advances in technology. For example, a recent estimate suggests that the cost of producing synthetic crude from coal via the H-coal process is now as low as $35/bbl (Lumpkin 1988). Shale oil is now being produced in Colorado by UNOCAL Corporation at a cost of about $40 to $45/bbl.

In addition, many ways have been found to extend domestic conventional oil resources, including infill drilling (Fisher 1987) and enhanced oil recovery to extract more oil from presently producing formations. Because only about one-third of the oil originally in place is extracted on average using present methods, much may be gained by improved technology.



	USA	Rest of the world	TOTAL
Coal	38,000	115,000	153,000
Crude oil	500	6,600	7,100
Natural gas	600	7,800	8,400
Unconventional oil	500	8,600	9,100
Heavy oil	100	3,200	3,300
Tar sands	0	2,500	2,500
Enhanced oil recovery	400	2,900	3,300
Unconventional gas	1,300	8,300	9,600
Oil shale	11,000	16,000	27,000
Total	51,900	162,300	214,200

Fig. 2.11. **Resources of fossil fuels in the United States and in the world.** *Sources:* Crude oil, natural gas, heavy oil, tar sands, and oil shale resource, Masters et al. 1987; coal, Vol. 2; unconventional gas, enhanced oil recovery, and oil shale recovery, estimates by D. B. Reister.

Finally, this hemisphere has huge deposits of heavy oils (in Venezuela) and tar sands (in Canada). These less conventional sources will be produced as the price of conventional oil rises and as the technology for producing liquids from these sources improves. About 200,000 bbl of oil per day are currently being produced from tar sands in Canada, although it is unlikely that any increase in production could be justified at current oil prices. Heavy oils are produced by steam injection in Canada and in California at prices apparently competitive in today's oil market.

From all of these sources, sufficient liquids can be supplied using both domestic and foreign resources to meet an even substantially increased demand. In fact, as shown in Fig. 2.12, a recent Chevron projection shows worldwide liquid use rising to some 150 quads by 2050 (25% greater than current usage), with prices from $6 to $9/million Btu (Fig. 2.13).

In summary, we are totally dependent on petroleum for transportation, and cheap petroleum is located in the Middle East. However, the United States is richly endowed with coal and oil shale, which could become abundant sources of liquid fuels as the price of petroleum increases and as conversion technology improves. In addition, domestic conventional oil resources can be extended signi-

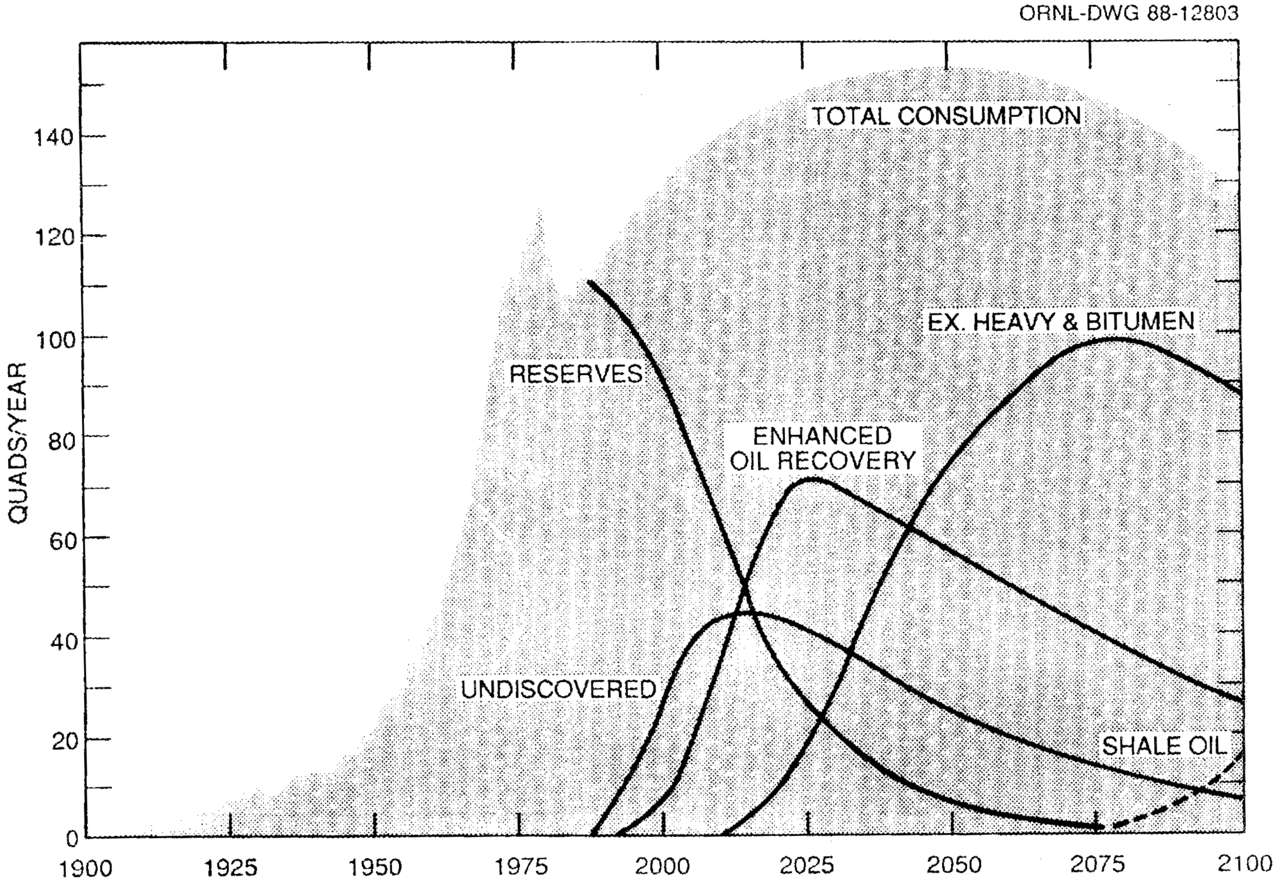


Fig. 2.12. World crude oil supply as projected by Chevron. *Source*: Redrawn with permission from *World Energy Outlook*, Chevron Corporation, October 1987.

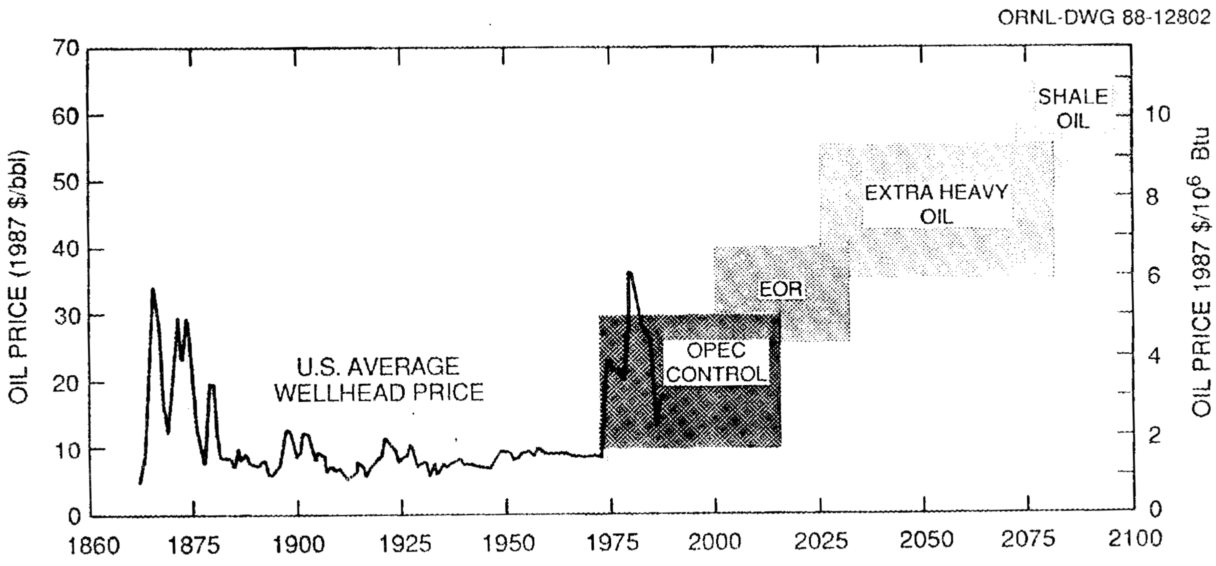


Fig. 2.13. Oil price outlook as projected by Chevron. (Constant 1987 dollars per barrel). *Source:* Redrawn with permission from *World Energy Outlook*, Chevron Corporation, October 1987.

ficantly by enhanced oil recovery and other advanced production techniques. Finally, large quantities of heavy oil and tar sands are found in this hemisphere, notably heavy oil in Venezuela and tar sands in Canada.

Natural gas

Natural gas is the cleanest burning of all the fossil fuels and, as a result, requires virtually no emission-control devices, provided that combustion is arranged to be complete and the temperature of combustion is not so high that significant quantities of NO_x are formed from oxidizing nitrogen in the combustion air. Often very little processing is required at the wellhead, except to separate hydrocarbon liquids and some impurity gases accompanying gas production. The products of combustion are CO_2 and water vapor (or condensed water) and small amounts of NO_x. Consequently, gas is an ideal fuel for use in buildings and in urban areas of high population density. It burns so cleanly that it can be used very efficiently because cleaning devices are not required. Extracting heat or mechanical work from the combustion process is straightforward because particulate matter that can cause erosion or clogging is absent and the products of combustion are normally not very corrosive, except for condensing water vapor. Various ways of dealing with condensate have been found.

Natural gas is readily transportable by pipeline or, at somewhat greater cost, in tanker ships as liquefied natural gas (LNG). LNG is produced by cooling the gas below the boiling point, -161°C, under a pressure of 0.14 MPa (1.4 atm). Compressed gas and LNG have been used to fuel highway vehicles, but on-board storage is expensive, and the range is much more restricted than for petroleum liquids.

Of course, natural gas can be converted into other hydrocarbon forms, and it is an important petrochemical feedstock. It can be converted into gasoline or methanol; this technique is being practiced in New Zealand, where methane is first converted to methanol, which, in turn, is converted to gasoline by the Mobil-MTG process (Musgrove 1987). This conversion entails a 30 to 40% loss of energy, most of which occurs in the conversion of natural gas to methanol (Salmon 1986; Salmon et al. 1980). Proposals have been made to convert underutilized methane, currently produced with oil and flared or sometimes reinjected, into methanol to use as a transportation fuel. Recent analysis indicates a maximum yield of about 4 quads of methanol worldwide from this source (Greene et al. Vol. 2, Sect.1.1.2).

However, natural gas, like oil, is a limited resource. Potentially recoverable resources of conventional gas in the United States are estimated to be about 600 quads, which is 35 times the current annual usage rate (Fig. 2.14). For all of North America, these numbers are 1200 quads and 60 years, respectively. Unconventional sources in the

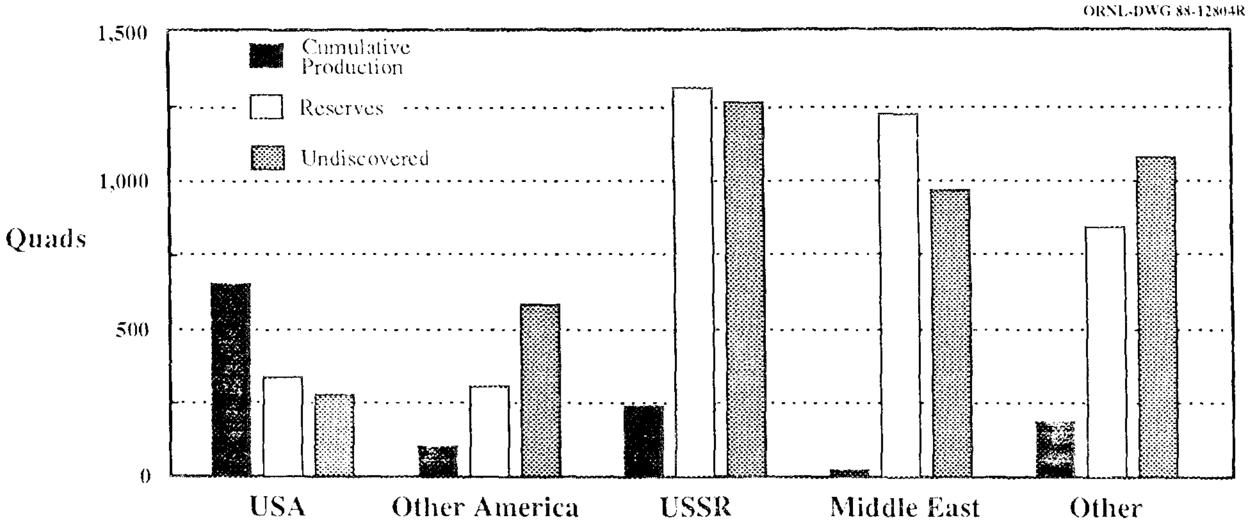


Fig. 2.14. World gas resources as of Jan. 1, 1985: Cumulative production, identified reserves, and undiscovered resources of natural gas by region (in quads). *Source*: C. D. Masters et al., *World Resources of Crude Oil, Natural Gas, Natural Bitumen and Shale Oil*, Twelfth World Petroleum Congress, Houston, 1987.

United States, such as tight sands and gas associated with coal, could add another 1300 quads, or 75 times the present annual use rate, if appropriate technologies can be developed. GRI has projected U.S. demand and supply of gas for the next quarter-century, as shown in Fig. 2.15 (GRI 1988). GRI projects that gas consumption in the United States will remain below 20 quads per year, with an increase in acquisition price from the present value of $2/million Btu to $6/million Btu by 2010. The projected supply mix in 2010 includes some 20% imports, mostly from Canada and Mexico. Also, some 25% of the supply is assumed to result from the application of advanced production technology, including recovery from tight formations and the development and application of enhanced gas-recovery techniques for all kinds of gas-producing geologic regimes.

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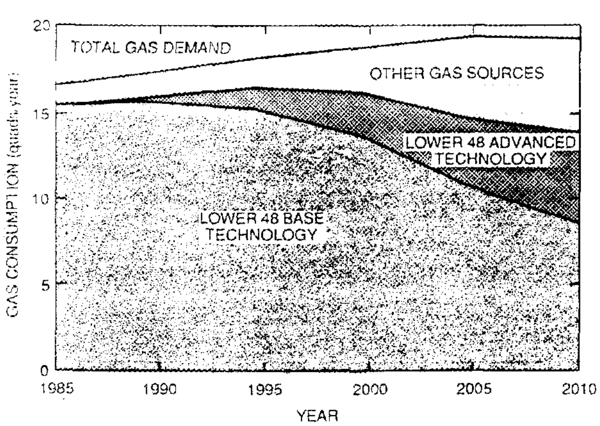

Fig. 2.15. GRI baseline projection of supply of gas. "Other Gas Sources" include imports from Canada and Mexico, LNG imports, coal gasification, and Alaskan gas. *Source*: Gas Research Institute, 1989-1993 Research and Development Plan, April 1988.

Worldwide conventional natural gas resources are estimated to be about 8400 quads, which is 135 times the present world annual use rate. Most of this gas is in the USSR and the Middle East, but a substantial amount is also found in other regions of the world, as shown in Fig. 2.14. Hence, the geographic distribution of natural gas is considerably different from that of oil. Thus, although gas is a limited resource, especially in the United States, sufficient quantities probably exist to supply it at present rates for a century or more worldwide and for many decades, even in the United States.

Because gas is such a clean, efficient fuel, its demand might be expected to grow rather than to remain constant. The American Gas Association (AGA) has projected a considerable increase in demand, owing to new or growing markets, including space cooling, compressed-gas-fueled vehicles, cogeneration, combined-cycle electricity generation, and cofiring of gas with coal and other dirty fuels to reduce pollution (AGA 1986). Balanced against these possible expanded markets are the potential improvements in the efficiency of gas use and the increasing price of natural gas, both of which would reduce demand. The improvement in the efficiency of gas-fired equipment has already been impressive, including pulsed-combustion furnaces and water heaters that achieve better than 90% first-law efficiency, compared with pre-embargo values around 60%. Very high efficiency gas turbines for electricity generation based on aircraft engine technology are now coming on the market.

In many uses (except transportation), gas is a good substitute for oil. For many industrial applications, especially process heat generation, for the generation of electricity by gas turbines or steam boilers, and for the supply of space and water conditioning for buildings, gas can substitute easily for oil products. Gas is also a good chemical feedstock. This substitution has two important consequences. The first is that gas gives the energy system some flexibility in the event of an oil shortage, an important energy security factor. The second is that the price of gas tends to be tied to that of oil.

As with liquids, gas of pipeline quality can be produced from coal. That is what is happening, with government subsidy, at the Great Plains plant in North Dakota, which is producing 125 billion Btu/day of gas for the pipeline. At today's gas prices, the plant is certainly no money maker, but it is operating well, and it is the only large-scale demonstration of such technology in the United States.

In summary, natural gas is the cleanest of the fossil fuels and can often be used more efficiently than other sources. It is a mostly indigenous resource, although imports from Canada and Mexico are likely to increase. The resource base, including such nonconventional sources as tight formations and coal-seam gas, is about 1900 quads or about 110 times the present annual use rate. The recent tendency is to consider gas an easy fix for some environmental problems and an expedient way to increase electricity supplies with a relatively low capital commitment. As a result, demand for gas

may grow, despite impressive improvements in the efficiency of technologies for its use.

Coal

From its mining to its burning, coal has the highest health-related and environmental costs of the major energy technologies. However, it is abundant, indigenous, and relatively inexpensive. Coal's share of U.S. primary energy consumption has grown from 17.5% in 1973 to 24% in 1987, largely because of its increased use in electricity generation (46% in 1973 to 57% in 1987) and to the growth of electricity generally. Burning of coal probably accounts for over 60% of SO_2 emissions and 30% of NO_x emissions. It is a major source of acid in the atmosphere. Worldwide, coal burning accounts for about 44% of the CO_2 emissions, gas for 16%, and oil for 40%. However, only coal is sufficiently abundant to increase atmospheric CO_2 by more than a factor of two (see Table 2.3).

Nevertheless, much has been done technologically to improve the use of coal, including ways to mine it that are less ecologically damaging, ways to reduce emissions, and ways to convert it to gases and liquids. Coal gasification is, in fact, being practiced around the country for various applications. It is used as a source of chemical feedstocks by Tennessee Eastman in Kingsport, Tennessee, and as a means for reducing SO_2 and NO_x emissions in the generation of electricity, as demonstrated in California by the Cool Water Plant, a joint effort of Southern California Edison, EPRI, the U.S. Synthetic Fuels Corporation, and various other partners, such as General Electric, Bechtel, Texaco, and a Japanese consortium. The Cool Water Plant benefits from recent advances in gas turbine technology. An attractive option for electric utilities is to increase capacity by incrementally adding very high efficiency gas turbines run on natural gas, either in a combined cycle with a steam turbine or with steam injection (Williams and Larson 1988), and backfit later with a coal gasifier when the price of natural gas increases.

Table 2.3. Estimated remaining recoverable resources of fossil fuels and their potential effect on atmospheric carbon dioxide

Fuel	Quantity	Energy content (10^{18} Btu)	Carbon content[a] (10^{15} g)	CO_2 concentration increase (ppm)[b] — Fraction of CO_2 retained in the atmosphere = 0.4	0.55	0.7
Oil	1255×10^9 bbl (0.2×10^{12} m^3)	7	130	24	34	43
Gas	8200 TCF (232×10^{12} m^3)	8	120	23	31	39
Coal	5500×10^{15} g	153	3850	723	994	1265
Total (rounded off)		168	4100	770	1060	1350

[a]In addition to these amounts of carbon, comparable or larger amounts may be available in other fossil resources such as heavy oils, oil shales, tar sands, lower grades of coal, etc. Thus, the quantity of carbon ultimately released to the atmosphere as CO_2 could conceivably be half again as much, or twice as much, as the total shown in the table.

[b]These hypothetical *increases* may be compared with the preindustrial CO_2 concentration (about 270 ppmv), the present concentration (350 ppmv), or the current annual increase (about 1.5 ppmv/year). In the atmosphere, 1 ppm of CO_2 by volume, uniformly distributed, equals about 2.13 Gt of carbon, or 7.81 Gt of CO_2. Thus, 350 ppmv CO_2 corresponds to 745 GtC. (1 Gt = 10^9 tonnes = 10^{15} g.)

Significant progress has been achieved with flue gas desulfurization (FGD) processes (or deacidification, if the process includes NO_x removal along with the SO_2 removal). These include wet scrubbing, spray dry scrubbing, and dry scrubbing stack gas processing techniques. The reliability and efficiency of such methods is improving, although much work remains to be done, and the disposal of solid residues is a significant problem. Also, FGD reduces the net efficiency of a conventional electric generating steam plant by about 5%.

Other approaches to NO_x and SO_2 emission reduction include fluidized-bed combustion and direct sorbent injection into the furnace (e.g., slagging combustors). NO_x emissions from fluidized-bed combustion are low because of the low combustion temperatures of the bed. Reduced NO_x emissions can also be achieved by various combustion modification techniques such as staged combustion, flue-gas recirculation, or reburning (e.g., with natural gas), which reduce the formation of NO_x, or by various downstream NO_x removal strategies such as selective reduction of NO_x (with or without catalysts) by injection of reducing agents such as ammonia, urea, cyanuric acid, or ammonium sulfate (see Heap et al. 1988 and NAPAP 1987). The latter strategies (selective reduction of NO_x in flue gases) can yield lower overall NO_x emissions but are likely to be more expensive and significantly increase emissions of N_2O, which contributes to destruction of the ozone layer. NO_x removal can also be combined with SO_2 removal by adding iron chelates to a wet alkali SO_2 scrubber, as in the experimental ARGONOX process (*Hazmat World* 1988).

As the national effort to control acid rain increases, these technologies will be applied generally. A recent study by DOE (DOE 1987c) argues that if aging coal-fired electric-generating plants are replaced by more efficient fluidized-bed combustion facilities or advanced integrated gasification combined cycle plants (an advancement over the Cool Water Plant), SO_2 and NO_x emissions can be reduced significantly, and at the same time, electric generating capacity can be increased due to the improved generating efficiency of the new technology. The overall cost will be comparable to that of extending the life of aging plants and retrofitting with FGD devices.

In summary, coal has serious environmental liabilities, but it is plentiful and cheap. Advanced technology is providing the means to use coal more cleanly and without a significant reduction in efficiency. As natural gas and petroleum become more expensive, coal can be used to produce substitute liquid and gaseous forms of hydrocarbons. One large unknown, of course, is what impact the greenhouse effect will have on the use of coal.

Nuclear fission

During the past 15 years, public acceptance of nuclear power and its attractiveness to electric utilities have been greatly diminished. In that time, no orders were placed for nuclear plants in the United States that were not subsequently canceled. This de facto moratorium was caused primarily by lower-than-expected growth in electricity consumption that led to excess generating capacity; but it was also caused in part by a combination of problems and issues, ranging from safety concerns (exacerbated by the Three-Mile Island and Chernobyl accidents) to escalating costs (partially related to safety), and to the difficult question of disposing of high-level radioactive wastes. Fully satisfactory technical fixes have not been forthcoming. However, steady progress is being made on nuclear wastes; passively safe or more nearly inherently safe new reactor types are being designed; and backfitting existing plants with additional safety systems is virtually completed. Institutional fixes, such as regulatory reform, have been controversial. As the de facto nuclear moratorium in the United States continues, the loss of infrastructure, including creative people to develop advanced concepts, grows. Despite these problems, nuclear power produced about 18% of the nation's electricity in 1987, which is more than from any other source except coal, and more than from oil and gas combined.

Great variability exists in the cost and operating experience of nuclear utilities across the country. Over the past decade, the "overnight" costs* of nuclear power plants have generally increased because of real increases in material, equipment and labor costs, but with a large spread around the mean (Hewlett, Cantor, and Rizy 1986). Operating costs (EIA 1988b) and capacity factors (the power pro-

*Overnight costs are the estimated costs in constant dollars as if the plant could be built overnight. Thus, financing costs are not included.

duced as a fraction of the rated capacity of the plant) have also varied greatly among U.S. nuclear plants. This large variability indicates both the difficulty of managing nuclear technology and the importance of potential improvements. In a recent report projecting the costs of nuclear plants compared with those of coal (Williams et al. 1987), coal was generally cheaper than nuclear when the comparison was based on the median cost of recently completed plants, but nuclear was generally less expensive than coal in most regions of the country when the comparison was based on the most favorable costs of recent plants of both types. This great variability in experience suggests that perhaps the industry tried to grow too fast (Crane 1988).

If nuclear energy is to be retained in the United States, several conditions need to be met (Crane 1988; Trauger et al. 1986):

1. The existing plants must be operated safely and reliably.
2. Waste management issues must be resolved.
3. A second generation of nuclear power plant must be developed that has passive safety features for increased protection of workers, the public, and the capital investment. The technology would be more attractive if it can be economically deployed in sizes much smaller than 1000 MW(e).
4. Standard designs for either the whole plant or all portions critical to safety must be licensable.

Whether these conditions are sufficient for the revitalization of nuclear power is unknown. That may depend to a considerable extent on what happens with competing, alternative energy sources, particularly coal. It should be remembered that around the world, including the United States, nuclear fission, hydroelectricity, and biomass are now the only large-scale nonfossil sources available; of these, only nuclear power is capable of growing to supply a substantial fraction of energy needs met today by fossil fuels, and at a roughly comparable cost.

Renewables

Since the Arab oil embargo, much attention has been focused on the so-called renewable energy sources. Most forms are either limited in availability and/or geography (i.e., geothermal, biomass, hydroelectric, ocean thermal energy conversion) or are intermittent (i.e., direct solar and wind). Nevertheless, the combination of these sources could play a more important role in the future, especially if the costs of fossil and nuclear energy rise. Direct solar radiation is, after all, one of the three large, virtually inexhaustible resources. Furthermore, although it is of low and variable intensity, it is ubiquitous; and it has great emotional and aesthetic appeal. Technological advances have been substantial, from improvements in the efficiency of wood stoves for heating the home to photovoltaics, the price of which has dropped by an order of magnitude or more in 10 years (see Fig. 2.16).

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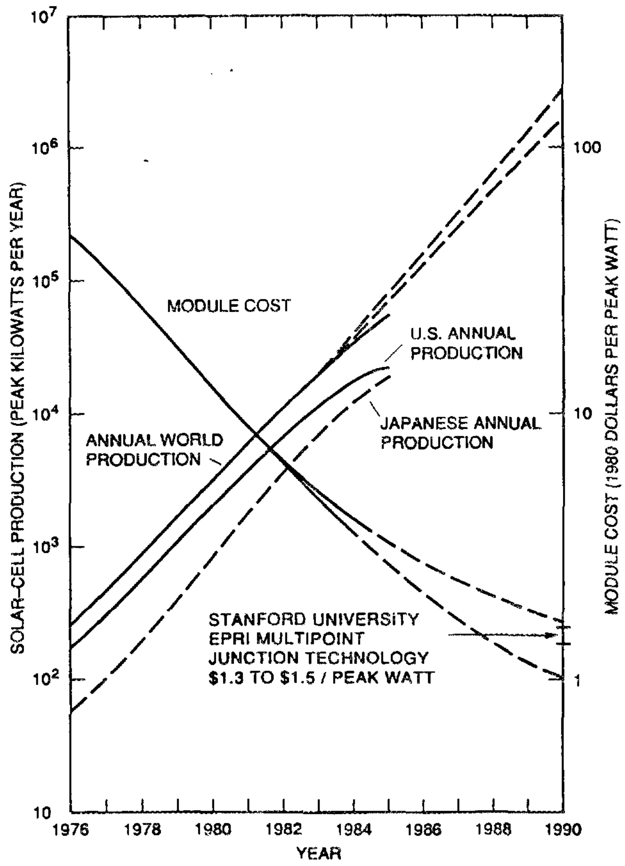

Fig. 2.16. Solar cell production and costs. *Sources:* from "Photovoltaic Power," Yoshihiro Hamakawa. Copyright © 1987 by *SCIENTIFIC AMERICAN, Inc.* All rights reserved. Vol. 256 (Issue 4), pp. 86-93 (April 1987); *EPRI Journal*, pp. 5-15 (Jan./Feb. 1987).

Biomass. In many parts of the world, biomass remains a major source of energy, mainly for warmth and cooking and mainly in traditional forms such as fuel wood, forest residues, and both agricultural and animal wastes. Worldwide, it contributes perhaps one-tenth of total energy supply. However, biomass has not generally been viewed as an important energy source for the future: dwindling supplies would be overwhelmed by increasing demand, and traditional forms would be poorly matched to the needs of more technically oriented societies.

That view may be changing. Emphasis is increasingly placed on conversion of biomass into energy forms—liquids and gases—that can be used more conveniently, more cleanly, and more efficiently. Furthermore, prospects for greatly enhanced productivity (mass per unit area per year) increase the likelihood that biomass can contribute significant amounts of energy in some industrial countries such as the United States.

Leaving aside food, biomass supplies 2 to 3 quads of energy annually in the United States, mostly for pulp and paper operations or for residential wood stoves. Ranney et al. (Vol. 2, Sect. 2.4.2) estimate that it should be possible to derive about 14 quads of high-quality fuels (mainly liquids) from 30 quads of feedstocks drawn from various sources, including commercial forests, forest residues, agricultural wastes, municipal solid wastes, wood and herbaceous energy crops, aquatic energy crops and others. The 14 quads is the net amount after deducting energy inputs required for acquisition and processing of the feedstocks. These amounts are not the maximum amounts that could be produced in the United States but rather the amounts estimated to be obtainable at costs only slightly above present fossil fuel costs and without seriously distorting markets for other commodities such as food and forest products. Thus, biomass might someday become an important source of liquid fuels for transportation if costs can be substantially reduced, and some steps in that direction have already been taken. During the late 1970s, government subsidies in the form of tax exemptions were introduced to promote the production of ethanol from corn as a gasoline additive (about 750 million gal of ethanol was used in gasoline in 1986). In Brazil, ethanol from sugar fermentation is used neat (without blending) in over 90% of all Brazilian autos sold since 1983. Assuming a 50% net efficiency of conversion from solid to liquid and accounting for the fuel necessary to cultivate and harvest the biomass, it seems feasible to produce 10 quads of liquid fuel in the United States. This quantity represents about one-half of the transportation fuel used today.

Hydroelectricity. Hydropower now accounts for 11% of U.S. electricity generation and a comparable percentage of installed capacity. Another 46 GW(e) capacity might be possible with acceptable environmental consequences. This number represents roughly a 50% increase in hydroelectric capacity. However, hydropower is a mature and nearly saturated resource in the United States, and such an increase would come with difficulty (Hildebrand and Kornegay, Vol. 2, Sect. 2.4.1).

Geothermal. Geothermal resources take numerous forms, including steam, hot water, geopressured brines, hot dry rock, and volcanic magma. Most are located in the western United States, except for the geopressured brines located along the Texas and Louisiana coasts. The total resource is enormous, but that which is economic is very small. At the Geysers in Northern California, about 2 GW(e) of electricity are produced from a steam-dominated hydrothermal reservoir. Considerable work is in progress to develop hot-water-dominated hydrothermal resources in the Imperial Valley of California (Mock 1988). Research in New Mexico by Los Alamos National Laboratory to develop hot dry rock technology is promising, and generalizable techniques are resulting (Whetten et al. 1988). The results from developmental wells into geopressured formations indicate the feasibility of producing methane and shaft power. Existing natural gas wells that penetrate into the geopressured region may prove the best means to establish an economic geopressured energy source (Whetten et al. 1988). Volcanic magma may prove to be a viable energy source in some locations, such as Hawaii.

Wind. Electricity from wind is an old idea, but the technology has improved enormously over the past decade with the application of advanced aerodynamic analysis, better materials, and better controls. Both horizontal and vertical axis machines are being developed. The DOE cost target for wind power is \$0.04/kWh(e) on the basis of 30-year levelized costs for machines operating where the average annual wind power is greater than 300 w/m^2. Present costs are probably in the range \$0.10 to \$0.15/kWh(e) (DOE 1985a). Areas of the country where wind power may be feasible include parts of the central plains, spots along the west and east coasts or offshore, and portions of the Appalachian

Mountains. Installed wind capacity in the United States at the end of 1983 was about 300 MW(e), much of which is on wind farms in California as a result of liberal tax credits and incentives (DOE 1985a). San Martin and Costello (1987) report that wind turbines with a combined capacity of 660 MW(e) were installed in 1985. By 1988, the total installed capacity in the United States was about 1.5 GW(e) (*Wind Energy Weekly* 1988). The problems with wind power are its intermittency, geographical limits, and noise, but in some places it may prove to be economical, especially if low-cost storage methods can be developed.

Solar thermal electric. Considerable progress has been made with a variety of solar thermal systems, including (1) distributed systems using parabolic dish or trough collectors focused on a heat collector containing a working fluid or a heat engine and (2) the central power tower concept, in which a field of heliostats is focused on a central receiver tower to heat a working fluid. These devices can produce electricity today in the desert southwest for a cost of about $0.12 to $0.15/kWh(e); the DOE R&D program objective is $0.05/kWh(e). Obviously, solar thermal technology can be used to produce process heat for industry as well as electricity. Currently, the installed capacity is around 300 MW(e), mostly in southern California near Barstow because of California tax credits. If solar thermal electric is used as a grid-connected fuel saver, saving natural gas, the gas would need to cost about $7/million Btu for the solar thermal electric to be competitive at the goal of $0.05/kWh(e). If, however, a capacity credit can be taken for the gas turbine for which the solar unit substitutes (because peak power demand and peak sun power coincide), then solar may compete if gas costs $5/million Btu.

Photovoltaics. Progress in photovoltaics has been impressive (see Fig. 2.16). Various configurations are under consideration, including flat plate "single-sun" and concentrating "multisun" devices. Many types of materials are under development, including crystalline and amorphous silicon, gallium arsenide, copper-indium-diselenide, and thin-film multilayered (multijunction) stacked cells of various design. For concentrating cells, the efficiency (electricity produced divided by the incident solar energy) is near 30%. For single-sun devices, it is near 20%. Currently, the system costs are about $0.40/kWh(e), but the DOE and EPRI goal is $0.06/kWh(e), similar to solar thermal electric (DOE 1987d). If this goal were met, a stand-alone system might produce power for a constant 24-h load at a cost of about $0.11/kWh(e) in the desert Southwest, assuming storage costs of $0.04/kWh(e) and a storage efficiency of 70%. That is still expensive power. Just as for solar thermal electric, the first applications of grid-connected photovoltaic power will likely be as a fuel saver in areas of the country where peak power loads correspond to peak insolation.

Nevertheless, photovoltaics can be applied at any scale (from powering a wristwatch up); they already have a market niche, providing a basis for further, incremental technological improvements and for realizing the economies of scale as these markets expand. Also, the systems tend to be rugged and durable and to require little maintenance. Therefore, photovoltaics are well suited to remote applications, where cost of grid connection is high.

Fusion

Like fission and solar energy, fusion has the potential to supply virtually unlimited amounts of energy. Furthermore, based on current information, fusion is expected to have smaller environmental and social impacts than those of fission. Nevertheless, despite substantial scientific and technical progress, a recent study by the Office of Technology Assessment (OTA 1987) suggests that commercial power from fusion is unlikely to be available until midway in the twenty-first century. Research is now directed towards reaching an assessment point in the next decade or two at which the feasibility and probable commercial attractiveness of fusion can be evaluated and decisions made regarding further R&D. Design studies and engineering cost estimates, indicating that fusion-derived electricity might cost approximately $0.05 to $0.08/kWh (e.g., Sheffield et al. 1986), have been used in setting goals for the program. Fusion may be regarded as an alternative or a complement to fission; it remains to be seen which of these long-term energy options may prove to be the more attractive in practice.

Electricity

Electricity is a marvelous energy form because of its versatility, high quality, and availability, and because the electric system can serve large or small loads on demand. It is a very controllable source, and it can therefore contribute to increased efficiency of end use. Electricity generation consumes a growing share of primary energy in the United States: from 27% in 1973 to 36% in 1987. Since 1970, the real price of electricity has increased 23%,

whereas before that time, the real price had dropped for many years. The price increase was the result of increased fuel costs and increasing capital costs, partially related to nuclear power plant construction, deferral, and cancellation. This change from declining to increasing marginal costs led to a significant slowing of the rate of increase of demand, but the demand still increased over the past several years at roughly the same rate as the GNP. It is possible that over the next several decades, technology advances will again cause the cost of electricity to decline (EPRI 1987a).

Because of uncertainties regarding load growth, long lead times, and high capital costs of coal and nuclear plants and because of changing and uncertain federal policies, a large fraction of new capacity added over the next 5 to 10 years will probably be fueled with natural gas, and some considerable fraction of that new capacity could be installed by so-called "independent power producers" rather than by electric utilities. Many interesting technologies may be used, including combined cycle, repowering of existing aging coal plants, various forms of cogeneration, and possibly even fuel cells. Also, significant progress has been made over the past 5 years in automating the electric transmission and distribution network, thus facilitating the wheeling of power, and in integrating many small sources (including cogenerators and wind and solar sources) into the grid. Automation also increases reliability by helping to locate faults and wire or route around them more quickly.

One of the most important developments of the past decade has been the realization by electric and gas utilities that both the supply and demand side of the market equation can be used to provide least-cost service. Thus, programs that encourage more efficient use of electricity and gas by the consumer, as well as peak-load shaving, can compete with new generating capacity. All sorts of arrangements, including time-of-use pricing and conservation incentives, are being used by utilities and encouraged by public utility commissions. The utilities have become among the most effective forces in marketing cost-effective efficiency improvements.

Summary

The period since the Arab oil embargo of 1973 has seen considerable improvement in both energy use and prospective source technologies. Furthermore, because these improvements are only now beginning or have not yet begun to penetrate the market, much of the impact of these changes will be felt in the future. R&D has produced a wide array of technologies, some of which not only convert and use energy more efficiently and economically but also do it more cleanly and safely. Clearly, the greatest impact was felt on the end-use side of the equation because the United States used 27 fewer quads of energy in 1987 than it would have used had energy intensity of the economy remained at the 1973 level. This reduction is three times as large as the increased contribution of coal and nuclear sources combined over the same period. The reduced energy intensity is due to both improved efficiency and to other changes such as shifting away from energy-intensive industries and modified behavior patterns. Furthermore, not all improved efficiency can be attributed to the adoption of new technology; some resulted from applying what had been known before the embargo. Still, much that is new was learned and applied as well. The progress in end-use energy efficiency since 1973 has been evolutionary, consisting of a "million quarter steps," but in aggregate, the results have been impressive.

2.3 INTERNATIONAL CHARACTER OF ENERGY

Obviously, energy is international, as the Arab oil embargo demonstrated so vividly. Oil is the key energy commodity in world trade; however, gas, coal, nuclear fuel, and electricity are growing in significance. Gas and electricity from Canada and gas from Mexico may become much more important to the United States. Certainly, an important development is gas supplied to Western Europe by the Soviet Union, and France has become an exporter of electricity as a result of its commitment to nuclear power. International shipments of nuclear fuel that contain plutonium raise concerns about the possible diversion of weapons-usable material. Finally, trade in energy technologies is a factor in international competitiveness. An often quoted fact is that we are losing the photovoltaic market share to the Japanese, and certainly we have lost much nuclear reactor and uranium enrichment business.

A very important international aspect of energy is the environment. Acid rain, possible global climate changes (e.g., the greenhouse effect), and the depletion of the stratospheric ozone layer are all in part a result of fossil fuel use and other energy-related activities, and the greenhouse effect and

ozone depletion are the same regardless of where the polluting activities take place. Nuclear safety is also an international concern, as Chernobyl proved. All these effects transcend national boundaries, and in the future, they may have the most profound impacts on the U.S. energy system. What one nation chooses to do to satisfy its energy needs clearly may affect another. It is the global commons question, and how to manage it will become an increasingly prominent issue.

In a sense, oil can be thought of as a global commons issue, too. If aggregate demand rises too rapidly or supply is reduced, price shocks may occur. Such shocks hurt everyone, particularly the non-oil-producing developing nations, and contribute to world political as well as economic instability. Thus, actions taken to moderate oil use, such as improved energy efficiency, whether taken in the United States or in a developing country, can have a positive impact on world stability.

Finally, energy R&D is becoming more and more collaborative among nations. Cooperation is needed particularly for very expensive, long-term R&D programs. Nuclear fusion research is an example. A commercial reactor is many decades away, but progress depends on ever bigger and more expensive machines. International collaboration may be needed to spread the costs. Even with less expensive programs, such as conservation research, collaborative programs speed technical progress. It may be noted that when the knowledge acquired through R&D is freely shared throughout the world, such collaborative cost sharing seems especially appropriate.

The next section deals with a range of projections for energy use and supply for the United States and the world. As this chapter emphasizes, the only appropriate view of the energy system is a world view. Interactions with the rest of the world are essential, and to understand what may make a difference in energy technology R&D, it is necessary to consider the whole system of which we are a part.

2.4 FUTURE ENERGY DEMAND

In considering requirements and opportunities for energy technology R&D, future energy demand is a major factor. How much energy will people want and be able to afford? In what form? How much will energy suppliers be asked to provide? The fact is that nobody knows. The great range of energy forecasts for the United States and for the world as a whole is not merely a matter of philosophical differences about how the world ought to develop; it reflects genuine large uncertainties regarding a host of factors that together will determine the future use of energy. We can, however, attempt to characterize these uncertainties, to establish a plausible range of energy forecasts, and to explore the implications of projections within this range for energy R&D.

Economic growth is the primary cause of expansion of energy demand and the corresponding expansion of supply. However, numerous studies and our experience over the last several years demonstrate that the ratio between energy use and economic output is by no means fixed. As Fig. 2.1 shows, that ratio for the United States, after remaining roughly constant for two decades, has declined 27% since 1970, largely in response to higher energy prices. Although future changes in the size and composition of economic output cannot be predicted accurately, the relationship between economic output and energy use, E/GNP, remains the largest source of difficulty in trying to forecast future energy demand.

Discussions of energy policy over the past 15 years have often focused on this point. There has been and to some degree there remains a fundamental disagreement between those who expect energy demand to continue to rise and are chiefly concerned with ensuring an adequate supply, and those who believe that it is both possible and advantageous to reduce E/GNP far enough and fast enough to support continued economic growth with little or no increase in energy consumption, and perhaps even a decrease, for at least several decades. Intermediate positions are also held. In truth, the uncertainties are quite large. Currently, a wide spectrum of possibilities exists, ranging from at least -1 to +2%/year average change in U.S. energy use over the next few decades.

These widely different expectations for the future result from different assessments (or assumptions) regarding future population trends, growth in the GNP, a changing mix of goods and services, changes in living and working patterns, energy prices, and especially the real prospects for reducing the energy intensiveness of activities in all sectors of the economy. The last factor, improved energy efficiency, is partly a matter of technical possibilities, partly of government policies (including tax policies

and regulatory standards) and partly of market forces (i.e., economic efficiency*).

The nominal bounds, -1 to +2%/year energy growth, are by no means absolute limits. Nor does one expect a constant rate of exponential growth or decline to continue for very long. Indeed, either +2%/year or -1%/year, continued for many decades, leads to a level of energy consumption that, from our perspective today, seems improbably high or low.

It is not our purpose to review projections for future U.S. energy use in much depth or detail. A few of these projections will serve to illustrate the broad range possible.

Two studies from the mid 1970s that explored a range of possibilities were the Ford Foundation's Energy Policy Project (Freeman et al. 1974) and the National Academy of Sciences' CONAES (Committee on Nuclear and Alternative Energy Sources) study (National Research Council 1979a). Projections from these studies are shown in Fig. 2.17(a and b), along with others that are discussed below.

The Energy Policy Project (EPP) considered three energy-demand scenarios for the United States for the years 1985 and 2000. All were based on full employment and steady growth in the GNP. The historical growth (HG) scenario assumes that energy use in the United States will continue to grow at 3.4% annually (the average rate from 1950 to 1970) and explores potential problems of energy supply that might arise with such continued growth. The Technical Fix (TF) scenario explores the potential for more efficient energy use through improved cost effective technologies. The Zero Energy Growth (ZG) scenario includes all of the energy-saving devices of the TF scenario and a small but distinct redirection of economic growth away from energy-intensive industries toward economic activities that require less energy. An energy tax would encourage a shift (by making energy more expensive) from making things to offering services.

From the perspective of 1988, all three scenarios seem high; but the TF and ZG scenarios are much closer to experience. In Fig. 2.17, the energy consumption estimated for the three scenarios is compared with historical data. For the three scenarios, the energy consumption in 1985 ranged from 88 to 116 quads. In 1985, the scenarios were high by 19 to 57%. In 2000, the three scenarios ranged from 100 to 187 quads. The conventional wisdom now is that U.S. energy consumption in 2000 will be less than 100 quads. In 1988, the EIA forecasts for 2000 range from 85 to 93 quads (EIA 1988c).

In the CONAES study, the demand panel analyzed six scenarios for 2010 based on different assumptions about energy prices and the GNP in that year (Table 2.4). Scenario A*, a variation of A, requires more aggressive government policies to reduce energy demand and more lifestyle changes.

Table 2.4. CONAES energy demand scenarios

Scenario	(2010 energy price) / (1975 price)	(2010 GNP) / (1975 GNP)	Average annual GNP growth rate (%)
A	4	2	2
B	2	2	2
C	1	2	2
D	2/3	2	2
A*	4	2	2
B'	2	2.8	3

Source: National Research Council 1979(a).

*In this report, we use the word "efficiency" primarily to mean "energy efficiency" or, loosely, the relative energy required to perform a certain task, but occasionally we use it to mean "economic efficiency," the optimal use of all resources; in the latter case, we say, "economic efficiency."

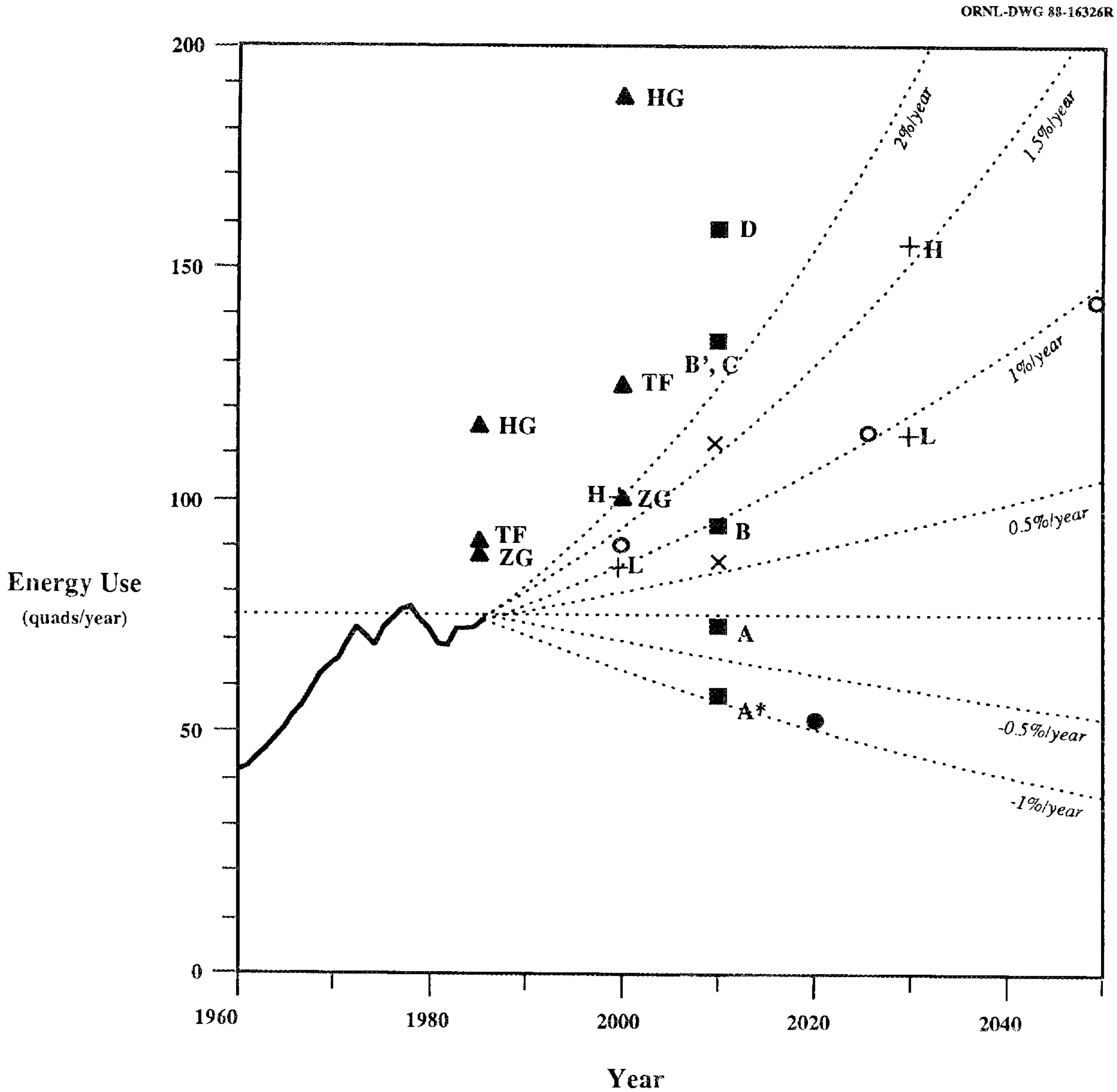

Fig. 2.17(a). Comparison of forecasts of total energy consumption in the United States. *Source of historical data*: EIA 1988b.

Explanation of symbols:

▲ Energy Policy Project, Historical Growth (HG), Technical Fix (TF), and Zero Energy Growth (ZG) scenarios;

▪ CONAES;

+ IIASA, High (H) and Low (L) scenarios;

× DOE, NEPP-V (see Fig. 2.9);

○ Edmonds-Reilly base case;

● Williams.

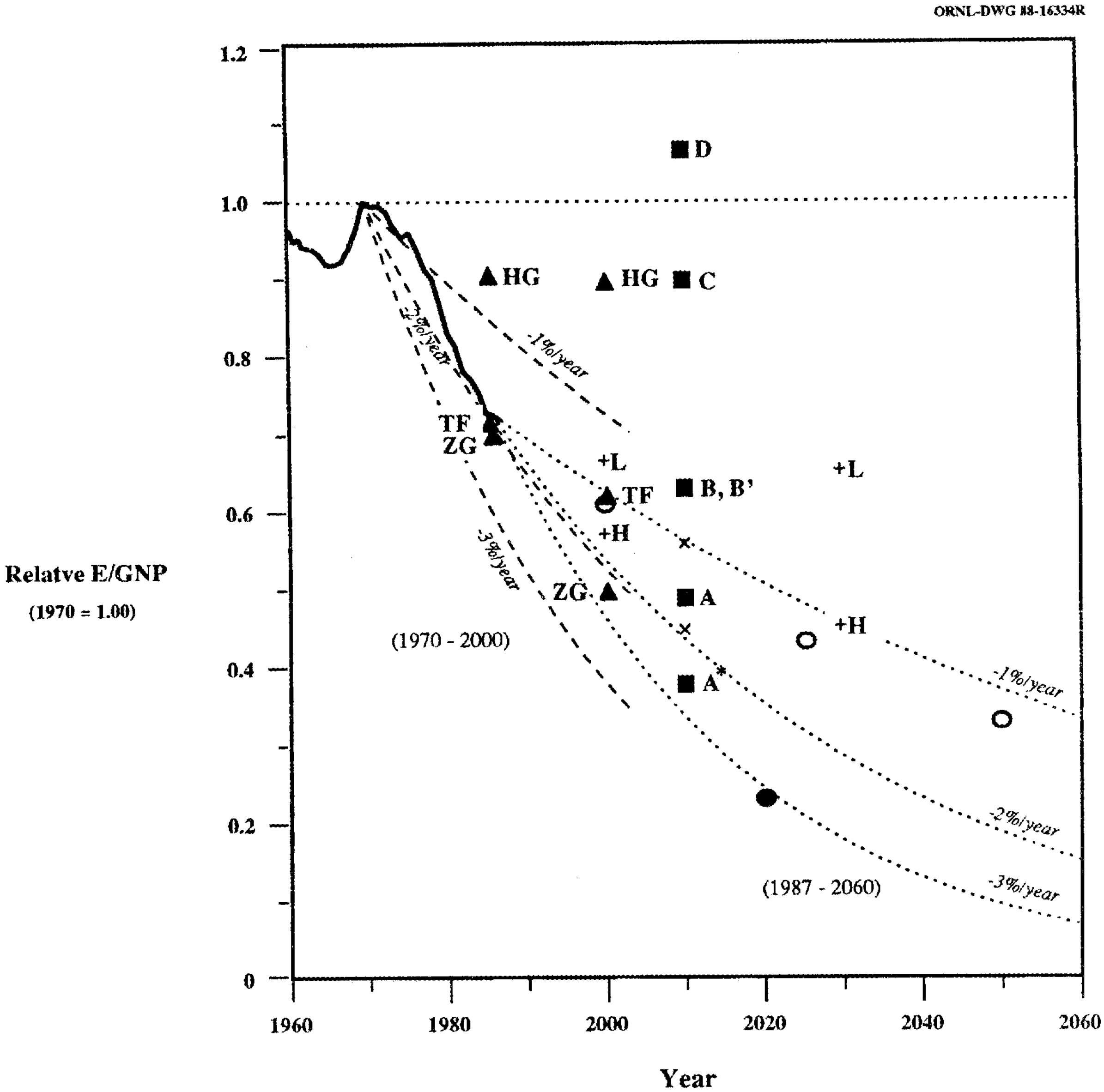

Fig. 2.17(b). Comparison of forecasts of the ratio of energy consumption and GNP in the United States. Historical data normalized to 1.00 for 1970. Dashed lines indicate exponential decreases starting at 1.0 in 1970; dotted lines indicate exponential decreases starting at 0.72 in 1987. Source and symbols: see Fig. 2.17(a).

As shown in Fig. 2.17(a), these different assumptions lead to a very wide range of energy use in 2010, from less than 60 to 160 quads. Since the GNP (but not necessarily the mix of goods and services) is the same in all of the scenarios except B', a correspondingly large variation in energy per unit of output (E/GNP) is implied, as shown in Fig. 2.17(b). Most of this variation is attributable to the large range of assumed energy prices.

The possibility of very large reductions in E/GNP in the U.S. economy (E/GNP) has of course been the subject of numerous studies over the past 15 years. One recent exploration of these possibilities is that of Williams (1987), who concludes that technologies now available or in an advanced stage of development should permit roughly a fourfold reduction in E/GNP and that such a reduction would be cost-effective at energy prices similar to those prevailing in the early to middle 1980s. Williams' analysis was not predicated on substantial lifestyle changes but did incorporate expected shifts in the composition of industrial output towards less energy-intensive products.

Williams' study involved explicit technical assumptions for the energy intensiveness of specific activities—for example, miles per gallon for automobiles, kilowatt hours for lighting, and percentage efficiency gains in heavy industry (Williams 1987). In contrast to this approach, the Edmonds-Reilly (ER) Model (Edmonds and Reilly 1986) is an energy market equilibrium model for the world, with the United States modeled as one of nine disaggregated, interacting regions. We have used it to explore trends in energy consumption over the time frame of our study, extending out to about 2050. The model establishes a detailed balance between energy demand and supply, the result depending on a large number of parameters characterizing supply and demand (e.g., elasticities and technical-change indexes). The GNP, however, is essentially an exogenous input, subject only to small adjustments within the model. Each of the parameters is described by a range of values derived from different assumptions or sources. The base case is one run of the model using median values of all these parameters. It should be noted that, with plausible variations in the parameters, this model can produce a range of projections as wide as that shown in Fig. 2.17(a). In the base case, with the GNP growing at about 2 1/2%/year, E/GNP declines at about 1-1/2%/year, and primary energy use increases about 1%/year. By contrast, in the Williams scenario, with roughly the same growth in the GNP, E/GNP declines at more than 3%/year so that energy use decreases at about 1%/year.

The International Institute for Applied Systems Analysis study (IIASA 1981) modeled North America (the United States and Canada) as one of eight world regions; the energy use shown in Fig.2.17(a) for the United States is 87% of that obtained by IIASA for North America. Explicit assumptions made in this study for future efficiency improvements for various activities and processes were less optimistic than others (Williams', for example). The higher energy use projected in the IIASA scenarios is a direct result of this assumed smaller improvement in the energy efficiencies of many different processes, modified in the case of the IIASA low scenario by a slower growth in the GNP. It is interesting that E/GNP declines more rapidly in the IIASA high scenario than in the low one [Fig. 2.17(b)] because of more rapid dilution of older, less efficient capital stocks by new more efficient stocks. Figure 2.17(a) also shows the energy use previously detailed in Fig. 2.9, projected by DOE for National Energy Policy Plan-V (NEPP-V) with and without the reductions in energy use that may result from current DOE conservation research.

The foregoing discussion deals only with energy consumption in the United States. But as we have discussed, our energy system is part of the world system, and the two are locked together. Consequently, we looked at a range of forecasts for the world. For our purpose, this range is well represented in Fig. 2.18, which shows a comparison of projections for world energy use in 2020 from Goldemberg et al. (1988), IIASA (1981), and the World Energy Conference (WEC 1983). The latter two projections embody somewhat greater population growth than that of Goldemberg et al., and equal or greater growth in per capita GNP, at least for the industrialized countries, as indicated in Table 2.5. But the main distinguishing feature of the projection of Goldemberg et al. is the very large (fourfold) reduction in E/GNP for the industrialized countries. Based on studies of the United States (Williams 1987) and Sweden (Johansson et al. 1983), Goldemberg et al. assume that per capita use of final energy (at the point of use, excluding conversion losses) can be cut in half in industrialized countries while per capita GNP is doubled. They also assume (with specific technologies in mind) that conversion efficiencies can be increased sufficiently to offset a substantial increase in the fraction of

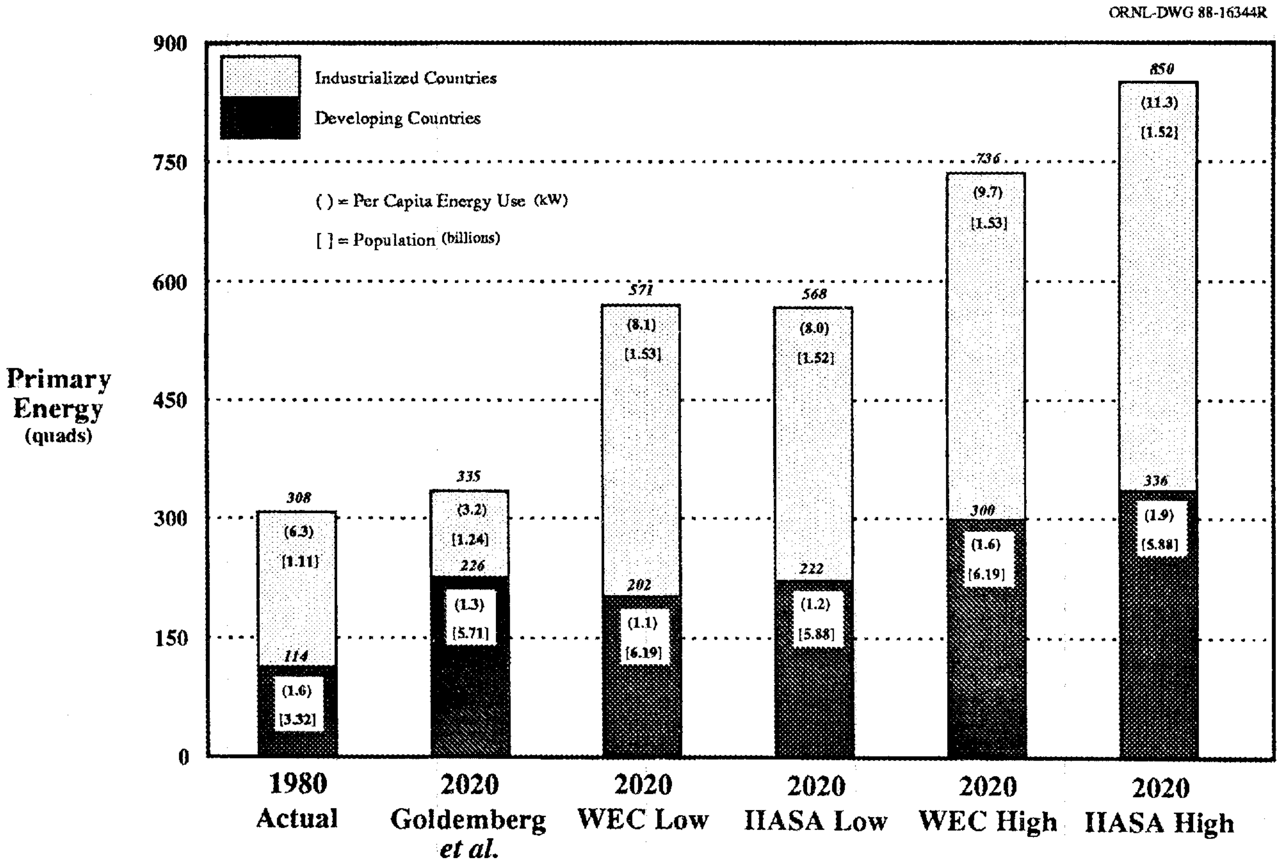

Fig. 2.18. Alternative projections of global energy use by industrialized and developing nations. *Source:* Goldemberg et al. 1988.

Table 2.5. Factors affecting energy growth to 2020

Scenario	Region[b]	Factors of increase, 1975-2020[a]					
		Population	(GNP/Cap)	GNP	(E/GNP)	E	(E/Cap)
IIASA high	A	1.3	3.3	4.2	0.6	2.5	1.9
	B	2.1	3.5	7.3	1.1	8.1	3.9
	W	1.9				3.4	1.8
IIASA low	A	1.3	2.0	2.7	0.7	1.8	1.4
	B	2.1	2.1	4.4	1.1	4.9	2.4
	W	1.9				2.3	1.2
Goldemberg et al.[c]	A	1.1	(2)	2.2	0.25	0.6	0.5
	B	1.7	?	?	?	2.2	1.3
	W	1.6				1.1	0.7

[a]Value of quantity in 2020 divided by value in 1975.
[b]A = industrialized countries; B = developing countries; W = world.
[c]1980 to 2020, 1980 = 1.00.

primary energy devoted to electricity generation. With respect to developing countries, Goldemberg et al. conclude from an analysis of a representative range of specific activities and processes that it should be possible, and economically desirable, for a prototypical developing country to raise living standards greatly, perhaps on average approaching that of Western Europe in the 1970s, with very little increase in per-capita final energy use. Nonetheless, total primary energy use by the developing countries more than doubles, and their share of world energy use increases from one-third to two-thirds.

The scenario of Goldemberg et al. requires that energy be used worldwide in 2020 as efficiently as the best technology now available (or soon to be available) permits. Whether or not one believes that such a scenario is possible, it does demonstrate one way that advanced technology of energy use could make a profound difference.

We do know that energy efficiency improvements of the type assumed by Goldemberg et al. are technically possible. For example, greatly improved refrigerators, heat pumps, water heaters, and other appliances are already appearing on the market, and even better ones are being tested. Vehicles with far better fuel efficiency than those now on the road have been tested, and not all of these involve loss of comfort or performance. Industrial processes are constantly being improved. Sometimes more efficient technologies cost more to acquire than the less efficient ones, but the efficient ones may have lower life-cycle costs. In some instances, life-cycle costs may be relatively small or nearly constant over a range of energy efficiencies so that a purchaser may prefer an option with the lowest first cost without regard for energy efficiency or may consider other attributes more important than efficiency. In short, these and many other factors, including ignorance, limited planning horizons, and nonmarket transaction costs, may limit the rate of adoption of more energy efficient devices. In addition, of course, some capital stocks remain in use for many years. Improving existing stocks via retrofits or early retirements may be less economically attractive than choosing more efficient stocks only as new ones are required. Finally, it may be that for some applications, devices or processes that are both more energy efficient and more economical will simply not be forthcoming at anything like current energy prices.

Some important nonmarket considerations, on the other hand, may favor the adoption of more energy efficient technologies. Many of these are obvious and well known. They include a broad range of environmental impacts, some not easily overcome by a simple technical fix. Climate change may prove to be the prime example. More elusive issues, such as continued dependability of energy supply, interregional and intergenerational equity, and the social acceptability of various sources of energy, may also enter the balance.

We are tantalized and attracted by visions of a low-energy future, like those of Williams for the United States and Goldemberg et al. for the world as a whole, that achieves vastly improved energy efficiency without sacrificing universal aspirations for a better life; and we cannot dismiss them as impractical, unattainable, austere, or socially and economically undesirable. Indeed, some further movement in this direction, beyond what has already been accomplished, seems virtually certain to occur although the rate of movement and the detailed character of the improvements are by no means certain.

We remain unsure whether improvements in energy efficiency will take place fast enough and far enough to offset the requirements of economic growth, leading to little or no growth in energy use, as indicated in Table 2.5 for the Goldemberg et al. scenario, or whether the balance will fall the other way and energy use will continue to grow but less rapidly than the economy.

From the perspective of this study, we should ask if it matters very much, in terms of appropriate energy technology R&D, whether energy use increases significantly over the next several decades or not. We will take up that issue in Chap. 4. In the meantime, we can anticipate that the issue of CO_2 emissions corresponding to these various energy scenarios will also be important.

The mix of energy sources for each of the scenarios in Fig. 2.18 is shown in Fig. 2.19. (For the WEC and IIASA scenarios, an average of the high and low scenarios is shown.) In 1980, fossil fuel use contributed about 76% of total energy supply (including biomass), and the CO_2 emissions from these fuels were 4.9 GtC/year,* of which oil contributed 51%. For the scenario of Goldemberg et al., oil use in 2020 is less than in 1980, but natural gas

*1 GtC = 1 gigaton of carbon = 10^9 metric tons (10^{15} g) carbon, contained in CO_2.

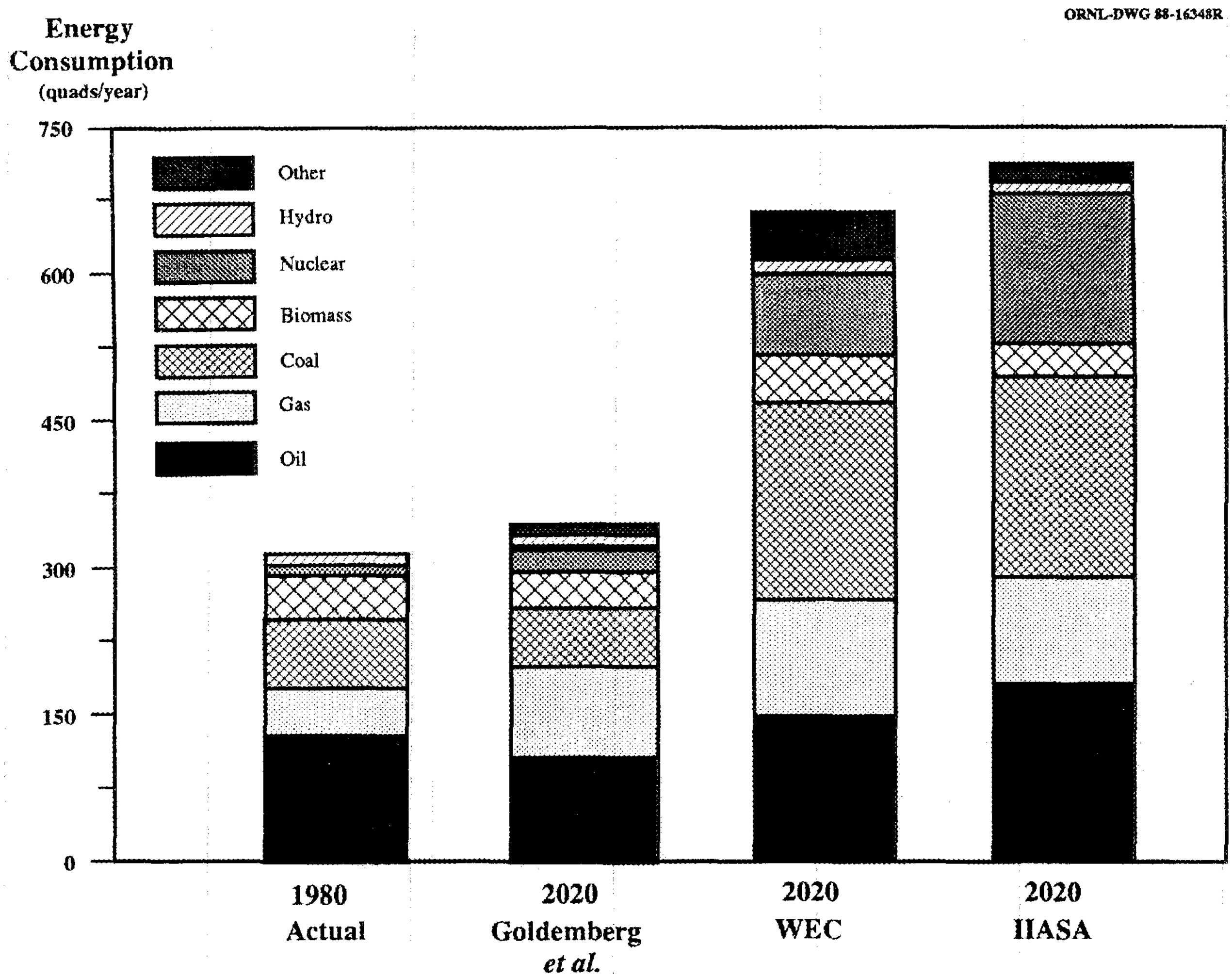

Fig. 2.19. Alternative projections of global energy use by source. *Source*: Goldemberg et al. 1988.

has become a major source, up 105% from 1980. Fossil fuels still contribute 76% of total primary energy supply, but CO_2 emissions, at 4.8 GtC/year, are slightly less than in 1980. In the composite WEC and IIASA scenarios, the use of all fossil fuels is higher than in 1980, and together they still contribute about 70% of a greatly increased energy supply. Coal use, in particular, is nearly three times greater than in 1980, and CO_2 emissions have doubled, from 5 to about 10 GtC/year.

To look at CO_2 emissions more closely, we turned again to the ER Model (Edmonds and Reilly 1986). This model was developed for DOE to create long-run (1975 to 2100) CO_2 emission scenarios for the world. The model is well documented and widely available, and it provides a useful framework for creating consistent scenarios.

We decided to use the ER Model to create two scenarios: a "middling" or midrange scenario, similar to the IIASA and WEC low cases, and a high efficiency case similar to the scenario of Goldemberg et al. For the midrange scenario, we used the ER base case discussed above, including this time, of course, the projections for the whole world, not just for the United States. To create a high conservation case, we followed a suggestion of Goldemberg et al. (1988) and changed the values of two key parameters (income elasticity and price elasticity) in the ER Model.

The primary energy supply for the two scenarios is displayed in Figs. 2.20 and 2.21. CO_2 emissions for the two scenarios are displayed in Fig. 2.22. As expected, the CO_2 emissions are much higher for the middling case than for the high-efficiency case, and half or more of the CO_2 comes from the combustion of coal. The high-efficiency scenario indicates the potential for using more efficient technologies to manage CO_2 emissions, as is discussed in more detail in Chap. 4 and Appendix C.

From the foregoing discussion, it is obvious that enormous uncertainty exists concerning what future energy demand will be. The range of forecasts we have highlighted is representative, but it does not bracket the world of possibilities. Furthermore, the difficulties of some energy system problems, discussed in the next section, are tied to how fast primary energy demand rises. It is fair to say, however, that the lower the demand, the smaller the problems that will need to be solved. Energy technology R&D can help achieve lower demand, and it can also help provide better technologies to supply whatever primary energy is needed. Finally, the common conclusions of all the forecasts are that fossil fuels are likely to remain the dominant energy sources for many years and that the need of developing nations for primary energy will grow very sharply.

2.5 ENERGY SYSTEM PROBLEMS - CURRENT AND EXPECTED

As we indicated at the outset and throughout this chapter, the energy system has a number of problems, some of which are chronic. In addition, it may suffer new difficulties, depending on how circumstances evolve. In this section, we review significant problems faced by the system now and some that it may face in the future. Some are recurring, such as sudden large oil price changes; others are ongoing, such as acid rain; and still others are specters of the future, such as the greenhouse effect.

2.5.1 Environment, Health, and Safety Issues

The tension between energy use and its adverse impacts on the environment and human health and safety goes on. Suffice it to say that energy is an essential means by which the human animal has improved his environment, health, and well-being; but the production and use of energy can also have undesirable effects, such as harmful emissions, accidents, scarred landscapes, conflict over resources, and so on. We review these and other problems at various geographical levels (global, national, regional, and local) and even at the level of the individual.

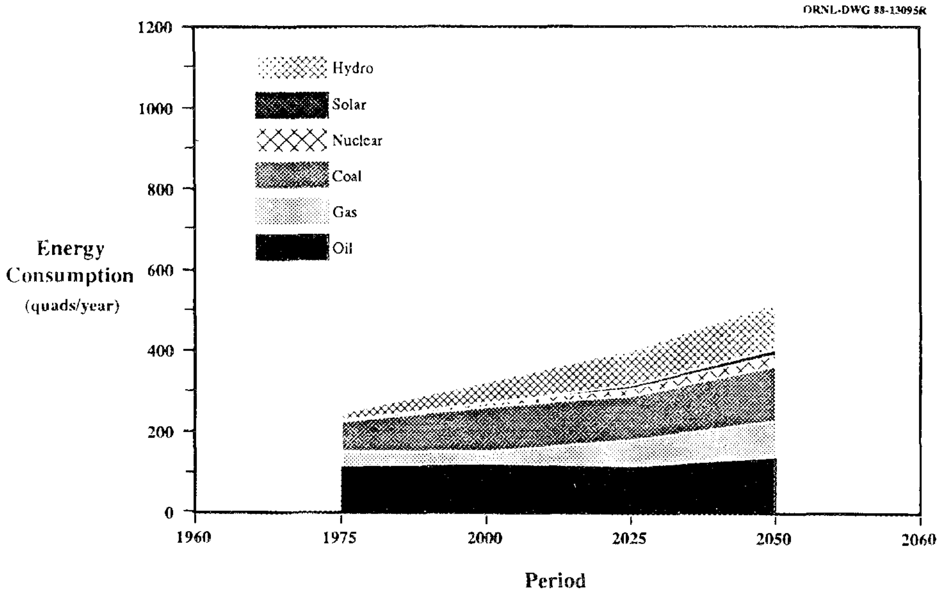

Fig. 2.20. Primary energy consumption for the high efficiency scenario. *Source:* Calculation by D. B. Reister using the Edmonds-Reilly model. Starting from the base case, the income elasticity parameters were reduced by 20%, and the price elasticity of demand parameters were doubled.

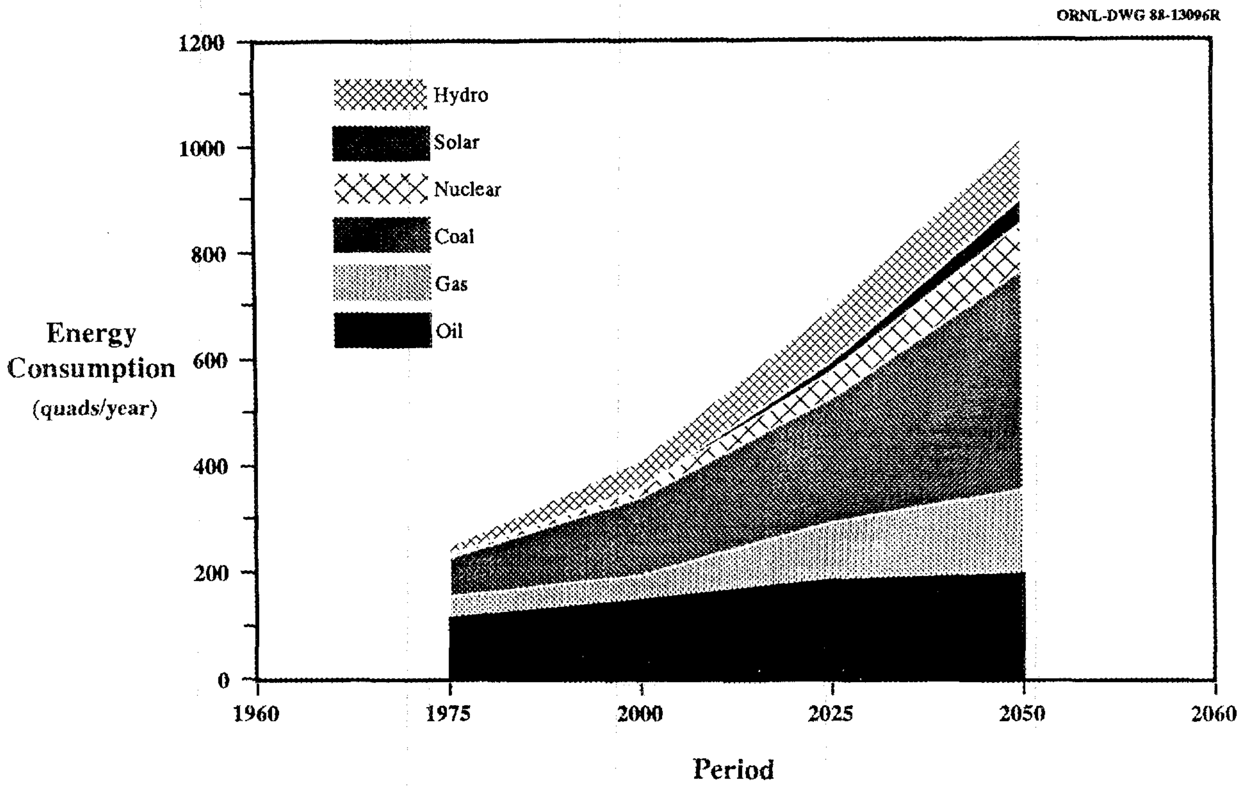

Fig. 2.21. **Primary energy consumption for the middling scenario.** *Source:* Calculation by D. B. Reister using the base case for the Edmonds-Reilly model.

For each problem, we ask what can and is being done to reduce the problem.

2.5.1.1 Global consequences of energy use

Three energy system issues appear to have a global reach: the greenhouse effect, stratospheric ozone depletion, and nuclear reactor safety and proliferation of fissionable materials.

The greenhouse effect. Of all the environmental issues arising from the production and use of energy, the so-called greenhouse effect may prove to be the most important and one of the least tractable. The term "greenhouse effect" refers to the warming of the earth's surface and lower atmosphere by the trapping of heat radiation. The absorption of infrared radiation by various gases in the atmosphere raises the temperature at which the earth can maintain an energy balance with incoming energy from the sun. Without this effect, the temperature of the earth's surface would be about 35°C colder on average than it is now, and life on earth as we know it would hardly be possible. Nevertheless, rather rapid changes in climate that could be induced by changing concentrations of the greenhouse gases present a worrisome prospect. Human societies and natural ecosystems have adjusted to current climate regimes. Of course, climate has changed greatly in the past (e.g., glacial and interglacial periods) and will do so in the future without our help. Nevertheless, prospective anthropogenic climate changes could create a warmer world than at any time during at least the last few million years. Futhermore, rapid changes, as may result from current trends in human activities, may tax adaptive capabilities, both human and natural, and could be extremely disruptive.

The most important greenhouse gases are water vapor (whose concentration is itself a function of temperature), CO_2, ozone (O_3), methane (CH_4), and nitrous oxide (N_2O), all of which are naturally present in small amounts in the atmosphere but whose concentrations are changing as a result of human activities. In addition, the man-made chlorofluorocarbons (CFCs) are also potentially important infrared absorbers. CFCs are used in refrigerators and heat pumps and in the manufacture of insu-

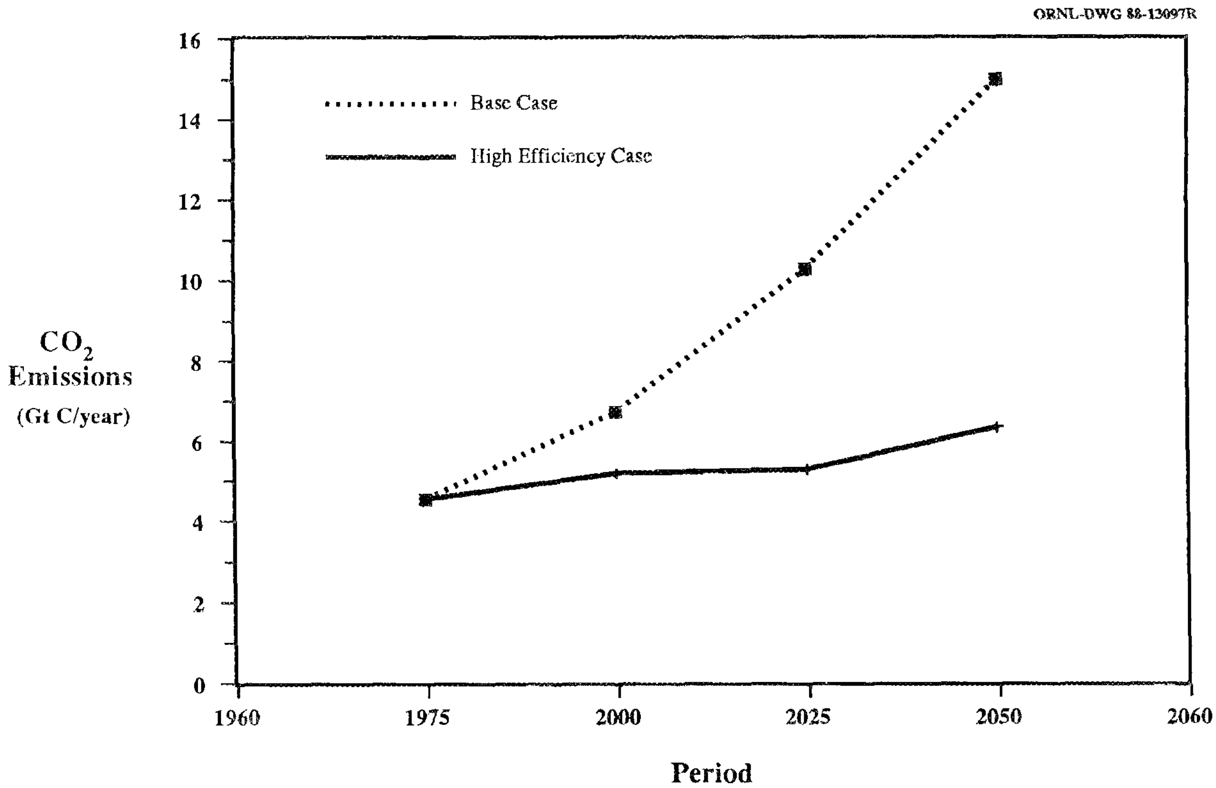

Fig. 2.22. Carbon dioxide emissions for the middling and high efficiency scenarios (in gigatons of carbon per year). *Source:* See Figs. 2.20 and 2.21.

lating materials and solid state electronic devices, such as photovoltaic cells. Hence, many uses of CFCs are energy related.

Of the previously named greenhouse gases, CO_2 is the most important one that is directly tied to human activities. The natural balance of CO_2 in the atmosphere is evidently being upset by two major human interventions: (1) the burning of fossil fuels and (2) reduction in the quantity of terrestrial biomass through deforestation and loss of organic carbon in disturbed soils. Presumably as a result of these interventions, the CO_2 concentration in the atmosphere has increased 25 to 30% over the past two centuries, from less than 0.03% of the volume of gases in the atmosphere to 0.035% [350 parts per million (ppm) by volume]. But more than half of that change has occurred within the past four decades, and the rate of change is still increasing: in the last 20 years, the rate of increase in CO_2 concentration has doubled, from about 0.7 ppm/year to 1.5 ppm/year.

The relative contributions of fossil fuel use and of land-use practices to this increase in CO_2 concentration are not easily determined. Fossil fuel burning now adds some 5×10^9 metric tons of carbon to the atmosphere each year as CO_2, a perturbation that may double over the next few decades, as noted in Sect. 2.4. In the past century or two, some 200 GtC have been released into the atmosphere by the combustion of fossil fuels and perhaps 100 to 200 GtC (net) have been released from the biosphere. Half of the total release from fossil fuel combustion has occurred within the last 20 years. The current net release of CO_2 from terrestrial biomass is estimated to be between 0 and 3×10^9 tons of carbon per year. The number is quite uncertain, however, because it is difficult to determine the extent to which the net loss of carbon from biomass in some regions may be balanced by the regrowth of forests in other regions. The large uncertainty in the net CO_2 source from the biosphere makes it difficult to use past experience to confirm models used in forecasting future increases in CO_2 concentration. Nevertheless, it appears that the CO_2 content of the atmosphere could double by the middle or latter part of the coming century if

fossil fuel emissions of CO_2 continue to increase as suggested by the upper curve in Fig. 2.22.

Doubling of the atmospheric CO_2 concentration is often taken as representative of changes large enough to have a major impact on human affairs and natural ecosystems. The principal effect is expected to be a climate change: up to a 5°C increase in global annual average surface temperature (with much larger warming at high northern latitudes in winter), marked changes in the amount and distribution of precipitation, large seasonal changes in average soil moisture, perhaps a greater frequency of extreme weather events associated with warmer weather such as droughts and more severe tropical storms—in short, a distinctly different climate regime to which existing patterns of human activity (including the energy system itself) and natural ecosystems may be poorly adapted. In addition, the warmer climate is expected to reduce the world's great masses of ice, which, together with thermal expansion of the oceans, would raise sea levels and flood coastal areas at a rate and to a degree that are now difficult to estimate.

Although CO_2 is the most important greenhouse gas that humans can control, it is not the only one. Atmospheric concentrations of the other infrared-absorbing gases named above are also increasing, and they can add significantly to the greenhouse effect, bringing much closer the time when the radiative equivalent of CO_2 doubling might be expected to occur. We estimate that CH_4, N_2O, and the CFCs together are currently contributing nearly as much to the annual change in the earth's radiation balance as CO_2 does. Relative contributions in the future will depend on future changes in emissions and concentrations of all the gases. These are even more elusive for CH_4 and N_2O than for CO_2 because their sources and sinks are not well known, a matter that we will not pursue in detail here. Suffice it to say that CH_4 in the atmosphere is mainly biogenic and is believed to come primarily from anaerobic processes involving cattle, rice-growing and wetlands, and from biomass burning. Some CH_4 may also come from coal mining and from the production and distribution of natural gas. Important sources of N_2O apparently include tropical and subtropical forest soils, oxidation of the nitrogen contained in fossil fuels (mainly coal), and, to a lesser degree, oxidation and/or reduction of nitrogen in agricultural fertilizers. Many of these sources of CH_4 and N_20 are related to or influenced by human activities.

To illustrate at least qualitatively some general dimensions of the problem before us, Fig. 2.23 indicates the amount of warming that might be expected under two different hypothetical scenarios for the greenhouse gases. In the scenario referred to as "Moderate Growth," CO_2 *emissions* increase as shown in the upper curve in Fig. 2.22; CH_4 and N_2O *concentrations* increase at rates close to the highest observed in recent years. In the curve marked "Low Growth," CO_2 *emissions* are held constant at the present level; CH_4 and N_2O *concentrations* grow more slowly, as indicated in the figure. For both curves, the CFC *emissions* are assumed to be reduced over a few years to about 50% of current levels, as proposed in the recent Montreal Protocol to the 1985 Vienna Convention for the Protection of the Ozone Layer. For both scenarios, 50% of the emitted CO_2, the "Airborne Fraction," was assumed to remain in the atmosphere. (This fraction might prove to be either greater or less than 50%; it will probably change somewhat over time, and it might well be greater for the "Moderate Growth" scenario than for the "Low Growth" one. Present knowledge is inadequate to resolve these uncertainties.) In Fig. 2.23, the climate-change parameter, τ, is not temperature per se, but rather the ratio of the rise in global average annual temperature to the corresponding rise that would be associated just with doubling CO_2, a quantity now estimated to be about 1.5 to 4.5°C (DOE 1985b). This approach suppresses the large uncertainty in the expected warming and is adopted because the relative effects of the various gases are thought to be better known than their absolute values. However, delays in actual temperature rise that would be caused by the great heat capacity of the oceans are not accounted for in this presentation; thus, Fig. 2.23 shows the relative *committed* temperature rise that would eventually result from the gases present in the atmosphere at a given time rather than the effect actually experienced at that time. Figure 2.23 shows the warming effect of changing concentrations of CO_2 alone, of the other greenhouse gases (CH_4, N_2O, and the CFCs) and of all of these gases together.

As Fig. 2.23 shows, stabilizing CO_2 emissions at present levels would not prevent a further increase in CO_2 concentration but would only slow the rate of increase. Tentative indications are that stabilizing the concentration would require roughly a 50% reduction in emissions (Firor 1988; Perry 1984). In any event, the other greenhouse gases would continue to produce a warming trend unless their con-

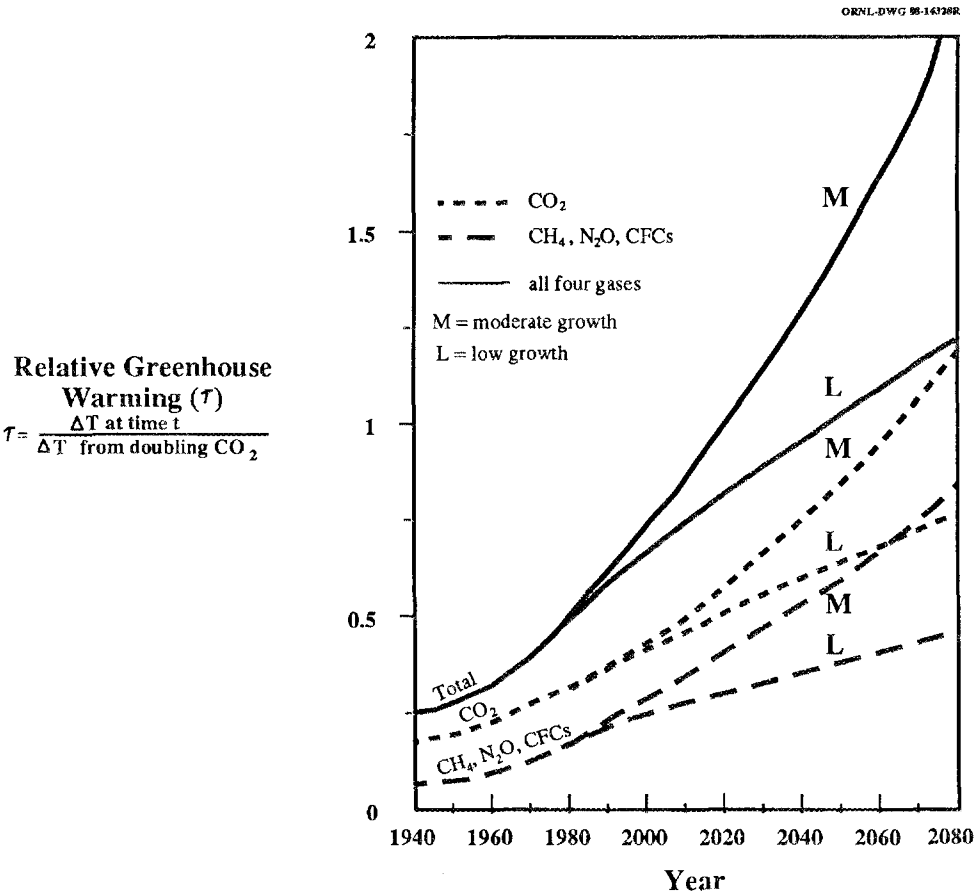

Fig. 2.23. Surface warming due to greenhouse gases. Increase in global annual average surface termperature, expressed as a multiple of the temperature rise from doubling CO_2, due to increasing concentrations of CO_2, CH_4, N_2O, CFC-11, and CFC-12 from preindustrial times. Time lags due to ocean thermal inertia are neglected.

Assumptions for the two curves are as follows:

	Concentration[a]			Post-1980 growth rate[b] (%/year)	
	Initial	1980	1988	Moderate	Low
CO_2	270	338	350	1.5	0
CH_4	0.8	1.6	1.7	1.5	0.75
N_2O	0.28	0.30	0.31	0.4	0.1
CFC	0	0.44	0.66	-3[c]	-3[c]

[a]Concentrations of CO_2, CH_4, and N_2O are in parts per million by volume; concentrations of CFC (F-11 + F-12) are in parts per billion by volume.

[b]Growth rates for CO_2 and CFC refer to rate of increase of emissions; these may be considered moderate to low (or negative). Rates for CH_4 and N_2O refer to increase of concentration. These may be considered high to moderate or low. The Airborne Fraction for CO_2 was assumed to be 0.5.

[c]Emissions decrease 3%/year from 1983 to 2010, then hold constant at 45% of 1983 emissions; this approximates the reductions called for in the Montreal Protocol of 1987.

For CO_2: $\tau = \ln(C/C_0) \div \ln 2$; $C_0 = 270$ ppm

For CH_4: $\tau = 0.33(\sqrt{C} - \sqrt{C_0})$; $C_0 = 0.8$ ppm

For N_2O: $\tau = 0.97(C^{0.6} - C_0^{0.6})$; $C_0 = 0.28$ ppm

For CFC: $\tau = 0.085C$; $C =$ F-11 + F-12 (ppb) ; $C_0 = 0$

centrations could also be stabilized. It is not yet clear what actions might accomplish that result, because the reasons for the present upward trends in CH_4 and N_2O concentrations are not well understood.

If the reductions in CFC emissions called for by the Montreal Protocol are implemented, CFC concentrations would eventually stabilize at two to three times the present values, and their contribution to the greenhouse effect, although not quite negligible, would remain small (i.e., τ about 0.15). This outcome is assumed in Fig. 2.23. However, if CFC emissions are not controlled and increase appreciably above present rates, CFCs could become major contributors to future global warming (See p. 47 on stratospheric ozone depletion).

Also note in Fig. 2.23 that in both the "Moderate Growth" and the "Low Growth" scenarios, the contribution of the other greenhouse gases advances by more than four decades the time when "equivalent doubling" of CO_2 takes place (i.e., when $\tau = 1$). For the Moderate Growth scenario, that date is advanced from about 2060 to 2020. Although these calculations are probably not correct in detail, the general message is valid: the time is not far off when significant climate changes may begin to be evident.

Further note in Fig. 2.23 that given the stated assumptions on initial concentrations of these gases—that is, the starting points for measuring changes in their warming effects—the cumulative effects of the other gases are now still much smaller than that of CO_2. However, the current rate of change of their combined effect is about the same as that of CO_2, effectively doubling the annual increase in the warming effect of CO_2; thus, τ is presently increasing by about 0.10 to 0.12 per decade.

A puzzling aspect of Fig. 2.23 is the rather large value of τ found for the present (i.e., about 0.6). If $\tau = \Delta T/\Delta T_2$ is this large, and if ΔT_2, the temperature rise associated with doubling CO_2, is as large as 3°C or larger, why hasn't a much greater change in global average temperatures been observed? During the past century, global annual average temperature has increased about 0.7°C (Fig. 2.24), not 1.5 to 2°C, as might be expected from Fig. 2.23. Several possible explanations can account for this apparent discrepancy. The temperature rise for CO_2 doubling may be smaller than is now believed. The initial concentrations chosen for our computations might be too low. The great heat capacity of the oceans may delay for several decades the full temperature response to a change in the radiation balance. Finally, other natural causes of temperature variations may temporarily mask the greenhouse effect.

This last explanation is particularly intriguing. In addition to short-term, seemingly random fluctuations in temperature, systematic longer-term variations appear to be associated with various identifiable natural causes (Bell 1988). More than a decade ago, Broecker (1975) pointed out that periodicities observed in ^{18}O measurements in a Greenland ice core strongly suggested that the downward trend in temperatures observed from 1940 to 1970 (Fig. 2.24) would be reversed during the latter part of the century. Then the CO_2 effect, no longer masked by a natural cooling trend, would instead be augmented or at least not compensated by natural, cyclic variations, even as the CO_2 effect becomes stronger because of expected increases in fossil fuel use. Bell (1988) has updated and extended Broecker's observation and has reached much the same conclusion. This explanation by itself is probably not sufficient to account for the apparent discrepancy between observed and expected temperature changes, but taken together with ocean thermal lag, it may do so. If so, we may expect the upward trend of temperatures over the past two decades (Fig. 2.24) to continue.

There are two schools of thought about coping with the greenhouse effect. They may be referred to as adaptation and avoidance, or prevention. The prevention strategy—preventing the climate change from occurring—includes actions to limit increases in the atmospheric concentrations of CO_2 and other greenhouse gases and actions to offset the warming effects of those increases if they do occur. The latter actions might include efforts to increase the earth's albedo, or reflectance, to compensate for the increased absorption of infrared radiation by the greenhouse gases. Such an approach seems risky and has certainly not been adequately evaluated.

Limiting the increase in CO_2 concentrations may be accomplished by restricting emissions of CO_2 from fossil fuel combustion and from deforestation, by a very large scale reforestation program (Marland 1988), or by capturing CO_2 from large point sources, such as coal-fired power plants, and disposing of it in depleted gas wells or in the depths of the oceans (Steinberg et al. 1984). Reforestation has limited potential but may be useful as a partial remedy. Sequestering CO_2 from coal combustion does not at

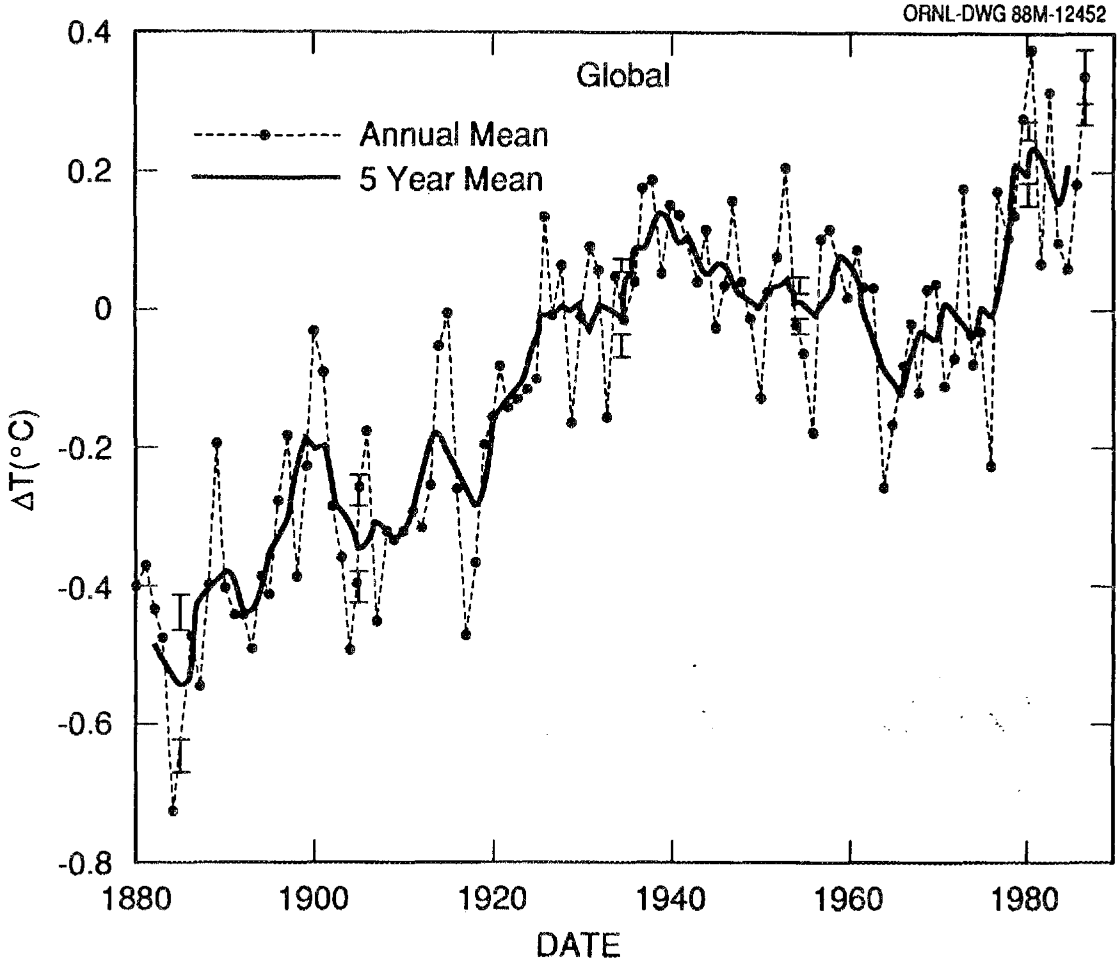

Fig. 2.24. **Global average temperatures over the past 100 years.** Source: James Hansen and Sergej Lebedeff, "Global Surface Air Temperatures: Update Through 1987," *Geophysical Research Letters* 15(4) (April 1988).

present look very promising, but it deserves continuing attention because, if successful and not too expensive, it could be helpful in reducing CO_2 emissions. [Steinberg et al. (1984) estimated that removal and sequestering CO_2 would increase the cost of electricity from coal-fired stations, on average, by about 75%.] The principal means of limiting the increase in CO_2 concentration still appears to be restricting the use of fossil fuels and especially of coal and oil shale.*

Many people believe that fossil fuels are so essential for further economic development that significant further increases in CO_2 concentration cannot be avoided. Certainly some increase is inevitable. Hence, some climate change will occur, although it isn't at all clear how rapid and extensive the changes will be.

Our view is that both prevention and adaptation will be necessary: that some climate change will occur and we will have to adapt to it, but that large

*Relative CO_2 emissions from fossil fuels, per unit of energy, are approximately in the following proportions, with natural gas arbitrarily chosen as 1.0: gas, 1.0; oil, 1.3; coal, 1.7; shale oil, 2 to 4 or more, depending on shale composition and retorting method; liquids from coal, 2 to 4, depending on product and process; high-Btu gas from coal, 2.6 to 3, depending on process. Combustion of natural gas emits 13.7 gC/MJ (Marland 1982).

changes can be avoided, probably should be, and at some level probably will be. That is, the very large changes that would result from full exploitation of the world's fossil fuel resources (Table 2.3) will probably not be allowed to occur. Coal, in particular, and shale oil will probably not be developed to the extent that would eventually occur in the absence of concern about climate change. However, the quantitative aspects of this question, although enormously important, are still lacking.

The problem of what to do about the increasing concentrations of other trace greenhouse gases has not been carefully evaluated except for the case of the CFC's. If the Montreal Protocol is implemented by the nations participating, the prospective increase of CFC concentrations should be much reduced. This action is not taken because of the greenhouse effect but because of the depleting effect of CFC's on stratospheric ozone, which is the subject of the next section. Nevertheless, implementation of the Protocol would markedly reduce the importance of the CFCs as contributors to the greenhouse effect.

As noted above, the reasons for the observed increases in CH_4 and N_2O concentrations are not sufficiently well understood to permit either a reliable forecast of their future concentrations or formulation of a strategy for limiting them. Limiting combustion of coal would presumably help to limit the increase of N_2O (Hao et al. 1987), whose contribution to the greenhouse effect in any case is relatively small. Increasing numbers of cattle, rice production, sanitary land fills, biomass combustion, coal mining, natural gas production and flaring all may contribute to increasing CH_4 concentration. In addition, changes in abundance of the OH radical (the principal sink for CH_4) can affect the CH_4 concentration. Release of methane hydrates from ocean sediments, which may be caused by global warming, could perhaps double the annual emissions of CH_4, and would be in addition to the other effects cited above. Since the greenhouse effect of CH_4 could be as much as one-third to one-half that of CO_2 (depending on growth assumptions), it is clearly important to learn more about factors affecting future CH_4 concentrations.

Stratospheric ozone depletion. Many of the chlorofluorocarbons (CFCs) are non-toxic, non-carcinogenic, non-flammable and very stable chemically. Hence, they are a most useful group of materials. Most refrigeration cycles, air conditioners, and heat pumps use CFCs as the working fluid. In addition, CFCs are used to make foam insulation and are used as solvents in the electronics industry. By means of all of these uses, CFCs eventually find their way to the atmosphere, and because they are stable, they are transported throughout the atmosphere, including the stratosphere. In the stratosphere, they are decomposed by the sun's radiation, and chlorine atoms are produced. These catalyze a cyclic set of reactions that destroy ozone. The net result is a depletion of stratospheric ozone. Ozone absorbs ultraviolet light from the sun. Its depletion in the stratosphere means higher levels of ultraviolet (UV) light at the earth's surface. The consequences of this increased UV include a greater risk of skin cancer and various effects on plant and marine life.

In September 1987 at a meeting in Montreal, 24 nations agreed to collectively curtail the use of halocarbons containing chlorine. If the agreed-to protocol is implemented, the potential problems with CFCs should be greatly reduced. In fact, there is currently much pressure to phase out the fully halogenated CFCs completely. The best substitutes available are chlorofluorocarbons or fluorocarbons containing hydrogen. These compounds have much shorter lifetimes in the atmosphere and have zero or much reduced ozone depletion potential, but they too can contribute to greenhouse warming. Hence, the business of finding adequate, more environmentally benign substitutes, either alternative chemicals or processes, is an active R&D topic. The net effect on the energy system is likely to be small in the long run, since it is generally believed that adequate substitutes can be developed for CFCs used in insulation and for refrigeration.

Nuclear reactor safety and proliferation of fissionable materials. The Chernobyl accident in the Soviet Union in 1986 produced more than radioactive fallout. It impressed on the world the fact that nuclear reactor safety is a global problem: first because radioactive emissions can be transported across national borders, and second because a nuclear accident anywhere causes great alarm everywhere. Nuclear power is special because of the large quantities of radioactive materials associated with it and because it uses or produces fissionable materials that could be used in nuclear weapons. For these reasons, it is a challenging technology requiring care and vigilance. Despite these characteristics, the nuclear industry has an excellent safety record. Nevertheless, as Chernobyl reminded us, a nuclear power plant can have a catastrophic accident. This possibility is of great public concern as demonstrated by the recent decision not to start the

Shoreham plant on Long Island because no agreement could be reached on an evacuation plan.

Because of these concerns, a number of countries are attempting to develop power reactors that do not rely on active safety systems. These new reactor concepts involve passive safety; that is, the reactor will shut down automatically without any operator intervention in the event of a failure in the coolant system, and the reactor will not overheat regardless of whether the emergency cooling systems work or not. Such reactors, if they can be built economically, should be much more forgiving, and they will protect both the public and the capital investments. (The major loss caused by the TMI accident in 1979 near Harrisburg, Pa., was financial; there was little physical harm to the public.)

The second global concern with nuclear power as it is adopted by more and more countries is the proliferation of nuclear weapons. Any power reactor is a potential source of fissionable materials that could be used for weapons although other sources of weapons-grade material are generally more attractive. Concerns focus largely, though not exclusively, on the reprocessing and recycling of plutonium, for which effective safeguards have yet to be demonstrated. Little economic justification exists now for reprocessing, but as the number of reactors continues to grow, uranium prices will eventually rise, and so will the value of the plutonium, leading to an economic incentive to recover and recycle the plutonium. Some persons concerned about proliferation might be prepared to accept a limited role for nuclear power that does not require reprocessing. However, the decision by France and Japan to reprocess spent fuel and ship recovered plutonium around the world (presumably to gain experience and facilitate waste disposal) underscores concerns that plutonium will be available, conceivably even to terrorist groups. The decision also underscores the fact that no unilateral action by the United States is likely to change the situation.

Technology can reduce the risks of proliferation or diversion but cannot eliminate them, especially under a reprocessing/recycle regime. Safeguarding measures can be improved, and reactor and fuel cycle designs that minimize the opportunities for the diversion of plutonium can be used.* However, if a country is willing to risk detection, no safeguards program can stop it.

Note that no country with nuclear weapons achieved them using power reactors. Rather, they built facilities dedicated to the production of nuclear weapons materials. This path is likely to be the preferred one for potential proliferators in the future. The main linkages to nuclear power plants are (1) plutonium in spent fuel could be used for a crash program to build crude nuclear weapons, and (2) a nuclear power program provides camouflage for a surreptitious weapons program and expertise that would be useful, if not crucial.

The major barriers to proliferation will have to be political, not technical. Nations must agree that nuclear weapons are not in their best interest. The Nonproliferation Treaty, now signed by 126 countries, states that signatories are not engaged in proliferation, thus reducing the incentives for their neighbors to do so. The treaty is enforced by the International Atomic Energy Agency through voluntary inspections of nuclear facilities. However, several countries of particular concern have not ratified the treaty, including Israel, South Africa, Pakistan, India, Brazil, and Argentina.

Proliferation will be an issue in any debate over a nuclear power revival. Under some conditions, a nuclear power program could contribute to a nation's nuclear weapons program, and plutonium reprocessing/recycle clearly creates the possibility of opportunities for diversion by terrorists. The severity of these risks is a matter of judgment that cannot be validated conclusively.

2.5.1.2 Multinational consequences of the energy system

Acid Rain. The quintessential example of energy system pollution emitted from one country, causing adverse impacts in another, is acid rain and the growing controversy between the United States and Canada and among European countries. "Acid rain" is a generic term describing both wet and dry acidic deposition from the atmosphere. Both SO_2 and NO_x emissions are converted to acids by chemical reactions in the atmosphere (National Research Council 1983). The evidence thus far supports the conclusion that acid deposition is mainly anthropogenic in origin, with electric utilities contributing over 50% of the precipitation acidity (Adams and Page 1985). Although scientific uncertainty over the cause and

*Alternative fuel cycles could be used to make diversion more difficult (e.g., Th/^{233}U because ^{232}U, inevitably present to some degree, emits a hard gamma ray).

effect relationships between acid deposition and the environment still exists, scientific evidence is accumulating that emission byproducts are having deleterious impacts on lakes, streams, and forests. (National Research Council 1986; Schindler 1988). Recent reviews (Schindler 1988) have suggested that the prevention of further damage or deterioration of eastern lakes will require at least a 50% or more reduction in current deposition loadings of SO_2. The relationship between emission rates and deposition loadings is complex and depends on location, atmospheric transport, and complex atmospheric chemistry. It is these uncertainties, in part, that have made it difficult to agree on SO_2 emission reductions. While the evidence for SO_2 effects on forests is more equivocal, some evidence indicates that reduction in forest growth and other types of damage are associated with overall air pollution.

Congressional concerns over acid precipitation resulted in legislation that created a 10-year national program (U.S. Congress 1980) charged to (1) identify the causes and effects of acid precipitation and (2) identify actions to limit or ameliorate its effects. This program, the National Acid Precipitation Assessment Program (NAPAP), is charged with providing information by 1990 to serve as the basis for policy recommendations on acid rain controls (General Accounting Office 1987). Numerous independent legislative initiatives have been proposed for regulating emissions that would place some constraints on the use of coal. Most recently, Congress has passed legislative proposals that would provide cost sharing for the development and deployment of new clean coal technologies. (U.S. Congress 1988b; EPRI 1988a). As a policy issue, acid precipitation will continue to remain on the legislative agenda, and the current active support for controls on emission of precursors of acid deposition strongly suggests that Congressional action is likely within the next few years. The final specific provisions of legislation will remain uncertain until a bill is enacted.

Enactment of stringent emission controls on SO_x and NO_x would shift a portion of potential coal demand to other fuels. What is uncertain is the rate at which new generating stations using clean coal technologies could be brought on line to replace 30 to 40 year old facilities for which emission controls would be too costly (DOE 1987c).

2.5.1.3 National consequences of the energy system

The health, safety, and environmental impacts of various fuel cycles are national concerns, and these are reviewed here briefly, especially those associated with various electricity technologies. For a more complete discussion, see the DOE Energy Technologies and the Environment, Environmental Information Handbook (DOE 1988a).

All energy technologies have inherent health and environmental risks associated with their use. The origins and potential magnitudes of these risks are as varied as the technologies themselves. Any energy technology represents a sequence of steps or operations, each of which may be a source of impacts or risks. Therefore, a comparison of the relative benefits and costs of a particular technology should take into consideration the potential environmental and social liabilities that may exist at the different stages of a particular technology or in the total fuel cycle.

As Holdren et al. (1983) points out, an assessment of the comparative liabilities of energy systems would include at least the following classes of environmental and social effects:

1. injuries (fatal and nonfatal, occupational and public) from accidents or sabotage;
2. illnesses (fatal and nonfatal, occupational and public, somatic and genetic) from routine emissions and exposures;
3. damage to property;
4. diminution of well-being through disruption of ecosystems or climate;
5. aesthetic loss and nuisance; and
6. undesirable changes in sociopolitical conditions and processes.

Of all the energy sources, we have the greatest experience and therefore the most knowledge of the effects of fossil fuels. Operating experience in the fuel cycles of oil, gas, and coal has provided a strong base of information on their environmental and social impacts. Because of its long history of use, we have a great deal of experience and knowledge about the effects of coal. The general public and workers in a wide variety of trades are subjected to risks from coal production and use. These risks include accidental injury, respiratory disease, and cancer. Nevertheless, despite more than a century of study of the health effects of coal, great uncertainties still exist. The health risks of the coal fuel cycle include

those caused by mining, cleaning, transport, combustion, and conversion. Estimates of mortality, injury, and disease for the various parts of the coal and nuclear fuel cycles are listed in Table 2.6. These estimates are discussed in the paragraphs that follow.

Coal Mining and Cleaning. The major and most well-documented health effects of coal mining are occupational (Morris 1983). Health impacts result primarily from chronic exposure to coal dust (especially in underground mines), which may lead to black lung disease if chronic inhalation occurs. More obvious is the number of injuries or deaths that result from the different types of accidents that occur with regularity in underground mines. These effects have been diminished with improvements in underground working conditions brought on by recent federal legislation and by the shift toward more surface mining of coal. Both black lung disease and accident and injury rates are much lower in surface mines (Gotchy 1987).

Environmental damage has long been associated with coal mining and especially with strip mining. Aside from direct damage to surface areas, acid mine drainage from both underground and surface

Table 2.6. Comparison of potential health risks to the total U.S. population from the nuclear and coal fuel cycles [per GWy(e)]

Source of risk		Total mortality	Total injury and disease
		Nuclear Fuel Cycle	
Uranium Mining		0.36-0.52	4.6-13
Processing[a]		0.17-0.29	1.0-3.1
Power Generation		0.068-0.070	1.9-5.0
Transportation		0.01	0.06-0.17
Reprocessing		0.052-0.057	0.19-0.21
Waste Management		0.004	0.008
Catastrophic Accidents		0.04	0.15
	Totals	0.70-0.99	8.1-22
		Coal Fuel Cycle[b]	
Coal Mining		~1.6	~66
Coal Processing		~0.027	~3.4
Transportation		~2.2	~31
Power Generation		5-10[c]	50-100[c]
Waste Management		>0-1	>0
	Totals	8.8-15	150-200

[a]Includes milling, conversion, enrichment and fuel fabrication.

[b]Ranges in this table are the range of best estimate values in the list and do not reflect the *total* range in the list.

[c]These ranges are controversial; actual range could be zero to perhaps several hundred.

Note: 1 GWy(e) = 8.76×10^9 kWh(e). 1987: nuclear, 52 GWy(e); coal, 167 GWy(e)

Source: Gotchy, R. L. 1987. *Potential Health & Environmental Impacts Attributable to the Nuclear & Coal Fuel Cycles, Final Report,* NUREG-0332. U.S. NRC, Washington, D.C.

mines has been a major source of environmental impact. As a result of federal legislation, considerable improvement has been made in the past several years. Nevertheless, rigorous enforcement is required at both the state and federal levels to prevent such abuses in the future.

After being mined, coal must be cleaned to remove impurities before shipment. Water is the primary cleaning vehicle. Hence, wash water is acidified and contains traces of toxic heavy metals and other contaminants. The remaining solid waste is usually dumped in spoil banks or waste piles. These are subject to sliding and further leaching of deleterious substances into ground or surface waters. Moreover, the piles are subject to spontaneous fires. These fires in 250 million tons of burning waste in the United States are believed to contribute about 5% to the overall national burden of carbon monoxide (Christman et al. 1980). One possibility being explored is the purposeful burning of these wastes in a fluidized bed combuster to produce heat and power (EPRI 1988b). Deaths and injuries to coal processing workers are not insignificant. It has been estimated (National Research Council 1979b) that about 0.02 accidental deaths occur per GWy(e). The injury rate is about 3.4 per GWy(e) (Gotchy 1987).

Combustion of Coal. The combustion of coal has long been associated with health problems. As a result, many studies and analyses have been aimed at deriving valid quantitative estimates of the cause/effect relationships among health effects and the effluents resulting from the burning of coal. Nevertheless, although the air pollution produced as a result of coal combustion is recognized by health authorities as a direct cause of respiratory fatalities, no exact measure of their number exists. Many estimates have been made of the number of fatalities attributable to the combustion of coal in generating electricity (for which about 70% of coal combustion occurs). Estimates of excess deaths caused by SO_2 and sulfate exposures vary widely and range from 3 to 60 per GWy(e) (Holdren 1987). This range is equivalent to about 500 to 10,000 excess deaths per year nationwide. Another set of values is given in Table 2.6. Although these estimates are subject to considerable uncertainty, they are in qualitative agreement with a recent projection of life shortening made by Wilson (1987), who estimates that of the 2,000,000 people who die each year in the United States, 50,000 may have their lives shortened by air pollution. These human health impacts of coal burning will be significantly reduced as SO_2 and NO_x emission from central power stations and industrial boilers are reduced as a result of the national clean coal effort.

The Nuclear Fuel Cycle. The estimates given in Table 2.6 of human health and safety risks associated with the nuclear fuel cycle indicate that they are approximately a factor of 10 less than for coal. This result depends on a very low value for catastrophic accidents. Holdren (1987) shows a much greater range, from less than 0.001 to 60 deaths per GWy(e) from such accidents. To put such numbers in perspective, the number of delayed fatal cancers over the next 50 years that may result from the Chernobyl accident is estimated to be about 17,400, or about 0.003% of the expected number from all other causes. (Anspaugh, Catlin, and Goldman 1988). The accident resulted in 31 early deaths. If accidents as severe as Chernobyl were to occur as often as once in 1000 reactor years, then approximately 17 deaths/GWy(e) would be an appropriate estimate. [Worldwide cumulative operating experience with nuclear power reactors now totals about 2000 GWy(e).] However, such a high frequency for such severe accidents seems unacceptably and unnecessarily high. Nuclear power can and must do much better than that.

Risks from normal operations of the nuclear fuel cycle are certainly much less than for coal, although clean coal technology can narrow the gap significantly. Note (Table 2.6) that with the exception of accidents, the major sources of risk in the nuclear fuel cycle are from uranium mining and processing.

Nuclear and Other Hazardous Wastes. The permanent, safe disposal of residuals that are byproducts of energy generation or its associated fuel cycles is a major challenge. The mounting evidence of direct (e.g., sludge piles) or indirect (e.g., ground water pollution) environmental and health threats continues to fuel public concerns about the siting and operations of energy-related facilities.

In the case of nuclear wastes, the issue of long-term storage is still not fully resolved. Because it is impossible to guarantee that there will never be any leakage, however slight, over very long periods of time (e.g., thousands of years) the issue becomes one of providing convincing assurances that any radioactive leakage into ground or surface waters

that might occur over such long periods will remain below certain very low tolerance levels. A site for the first federal high-level waste repository has been selected, at Yucca Mountain, in Nevada, and the extensive tests and detailed analyses necessary to validate this site selection are under way. The same laborious process will be required at each new site, and it can be expected to be difficult, controversial and time-consuming. Nevertheless, most experts believe that safe disposal of radioactive wastes can be accomplished in any of several types of geological settings and that the required assurances will be provided to accommodate both the considerable quantities of radioactive wastes already in existence and the even larger quantities to be expected from future nuclear power operations.

Disposal of intermediate and low-level radioactive wastes may prove to be more troublesome in the long run than disposal of high-level wastes, because the volumes of material to be handled are very much larger and the number of disposal facilities to be licensed and monitored is much greater. The specters that have been created in the minds of the general public by past practices in hazardous waste disposal—by leaking disposal sites or waste burial grounds, either radioactive or nonradioactive—have resulted in a very negative reaction to the location of any such facilities in many communities.

The nation faces a tremendous and costly cleanup problem because of its past waste disposal practices. The siting of new facilities for residual disposal, be it fly ash, sludges from emission control systems, or mixed radioactive and hazardous chemical wastes, will be increasingly restricted and costly. The reduction of health and environmental risks associated with disposal and siting practices will require the application of new sociotechnical approaches, such as recycling and front-end modifications to reduce end-of-pipe disposal requirements. Although remedial action activities will exact a large and necessary cost over the next decade, it is to be hoped that out of that investment, new attitudes, approaches, and technologies will emerge that will minimize the formation of residuals or lead to new concepts for treatment and disposal.

Other Energy Sources and Technologies. Environmental and health impacts are not limited to the fossil fuel or nuclear fuel cycles. No energy technology is free of potentially significant environmental hazards (Holdren 1987). These hazards are diverse and difficult to quantify, and in our present state of experience, they represent major challenges to arrive at measures of damage or risk. Recently, OECD has assessed the environmental impacts of renewable energy (OECD 1988).

Biomass. Occupational risks derive primarily from harvesting although they may be alleviated by the increased use of mechanized techniques. The other major direct hazard is indoor air pollution from the combustion of biomass without proper ventilation, which can be a problem in extremely tight, energy efficient buildings. This problem, as well as the emissions of unburned hydrocarbons in the outside atmosphere, can be greatly reduced by the use of properly designed stoves with catalytic oxidation enhancers. Other potential problems are deforestation, depletion of soil nutrients, and erosion, although proper management in an agroforestry setting can minimize these problems.

One of the potentially most exciting new opportunities and approaches that could make a significant difference in the role of biomass as a source of energy is the rapidly developing field of biotechnology or genetic engineering. Gene splicing, recombinant DNA techniques, and specialized tissue culture offer a powerful set of tools that may have profound influences on society, including the energy field. New types of plants that can fix nitrogen and resist the effects of pesticides are imminent. Selection for plants that are more efficient photosynthesizers and the mass cloning of such plants are within the realm of possibility. New microorganisms that will enhance nutrient uptake and growth of biomass are a distinct possibility.

The planned introductions of genetically engineered organisms into the environment are not without potential risks. A new organism that lacks ecological controls could multiply unexpectedly with undesirable consequences; subtle shifts and alterations in ecosystem balances may be brought about with a reduction in selective forces that have kept the systems in balance. The loss of genetic diversity in crops that have been engineered to precise criteria, although enhancing certain attributes, may make such crops vulnerable to unexpected biotic or climatic stresses. As a result of such recognized concerns, governments are moving toward regulation and imposition of careful controls on the use of genetically engineered organisms and especially their experimental release into the environment.

Hydropower. Because of natural or manmade causes, dams sometimes fail with serious loss to life and property. Also, hydroelectric facilities flood fertile bottom lands and may adversely affect both aquatic and terrestrial ecosystems. Dams may affect fish and biota by altering stream flow and oxygen concentrations downstream and by blocking the movement of fish during reproductive seasons. These are all well-known problems that may significantly restrict the further development of hydropower.

Photovoltaics. Each of the most promising semiconductor materials, such as silicon, cadmium sulfide, copper indium diselenide, and gallium arsenide, poses significant hazards of human exposure to toxic materials (Mintzer 1980). In the photovoltaic energy cycle, the principal potential impacts are health hazards to workers and possible environmental effects resulting from contamination of local water bodies by toxic substances during the manufacturing process. Workers may be exposed to dusts, fumes, or aerosols composed in large part of respirable particles containing quantities of those toxic materials.

The health hazards posed by the large-scale deployment of photovoltaics are significant but manageable with existing technology (Holdren et al. 1983; OECD 1988). The risks posed by the production and use of silicon cells are the least severe. The large-scale use of cadmium or arsenic in photovoltaic devices will yield both occupational and public health risks if these materials are released to the environment. Nevertheless, such problems are amenable to more or less standard abatement techniques.

Solar Thermal Electric (or Process Heat) and Wind Devices. The risk impacts of these technologies seem minimal although some problems exist with noise and rotor failure accidents of wind machines (OECD 1988).

Geothermal Energy. Geothermal energy systems have a number of potential health hazards that may affect workers and the public. From some sources such as the Geysers in Northern California, hydrogen sulfide emissions are a problem, although a controllable one. Other gases associated with the process, such as ammonia and radon, are considered to be issues of lesser magnitude. Hydrogen sulfide is a highly toxic compound and has been an occupational hazard in oil and gas fields. It can be fatal in short exposures to high concentrations (1000 ppm) and cause serious problems at lesser concentrations.

Two environmental hazards have been noted with geothermal systems. First, the escape of geothermal fluids that contain high concentrations of dissolved salts and toxic elements can affect nearby water bodies and supplies. Second, hydrogen sulfide oxidizes in the atmosphere to sulfur dioxide. It has been speculated that these would add to the atmospheric burden of this acid precursor in areas of intense geothermal development. However, most of these problems are manageable at some cost.

Fusion. Thermonuclear fusion is often said to be more benign than nuclear fission in terms of health and environmental hazards. However, at today's stage of development, too little is yet known about eventual designs, composition, and operation of these devices to make other than very general judgements. Fusion will involve radioactive materials that can pose threats to both workers and the environment. One of the primary fuel components will be radioactive tritium, which will also be produced in appreciable quantities at the reactor sites. This tritium inventory will pose hazards to workers at the site, will be subject to routine leakage, and could be released in larger quantities during an accident (Cannon 1983). The problem of tritium control will depend on details of fusion reactor design and could be comparable to or more demanding than the corresponding tritium control problem in fission reactors (Holdren et al. 1987).

The fusion process produces high-energy (14-meV) neutrons, which will produce a variety of radioactive isotopes in reactor components. The activated components may present an occupational hazard to workers and will have to be treated as radioactive wastes if they are to be disposed of at the end of their use. For pure fusion reactors, these problems are much smaller than those associated with fission reactors, but for fusion-fission hybrids, they are comparable. Pure fusion reactors also have a much smaller potential for serious accidents and much less potential for contributing to nuclear weapons proliferation.

Electromagnetic Radiation. Electromagnetic radiation from high-voltage power lines has become of concern because of presumed health effects resulting from chronic exposures to such fields. Many studies have been done on humans and animals, including epidemiological investigations of

the effects of power lines on local populations. These studies have yielded conflicting results (EPRI 1987b). Because of large remaining uncertainties, DOE and others are continuing studies of the biological effects of this type of radiation.

2.5.1.4 Local and regional consequences of the energy system

Several consequences of the energy system are felt and dealt with mostly at the local, state, or regional levels. These include localized air and water pollution problems, among which smog and related high concentrations of ozone and carbon monoxide have proved to be especially hard to overcome. Two other issues, primarily related to decision-making about new energy facilities, are management of land and water resources and the growing syndrome of "put it anywhere, but not in my backyard" (NIMBY).

Smog, Ozone, and CO. The smog problem is generally the result of growing traffic densities that exceed the carrying capacities of areas such as the Denver or Los Angeles basins. Sixty-five areas in the United States do not now comply with the National Ambient Air Quality Standards (NAAQS) for carbon monoxide, and 62 areas do not comply with the NAAQS for ozone (Swank 1987). These situations are partly caused by vehicle emissions in areas where meteorology is unfavorable for dispersion. The Clean Air Act (as amended) requires attainment of the NAAQS in all states by August 1988. Areas that failed to attain the standards by this deadline face more stringent emission controls. Without taking substantial new measures to reduce emissions, approximately 80 urban areas in the United States will be unable to attain the NAAQS for ozone or carbon monoxide (DOE 1988b) in the foreseeable future.* One such potential measure is the use of alternative fuels, such as methanol and ethanol in vehicles. Methanol is more likely to substitute for petroleum products as a basic fuel in vehicles, whereas ethanol will probably be limited to use as a blending agent in fuel because it is relatively expensive (DOE 1988b).

Methanol and ethanol emissions are mostly similar to gasoline emissions when used with the same emission-control equipment. Neat methanol- and ethanol-fueled vehicles emit unburned hydrocarbons of lower chemical reactivity than do vehicles using gasoline or diesel fuel (Alson, Adler, and Baines 1988). Thus, the formation of ozone, which consists of a complex series of photochemical reactions involving hydrocarbons and nitrogen oxides, is reduced. Nitrogen oxide emissions are reduced substantially because of cooler combustion (depending on engine design). Using fuel blends that contain alcohol at high altitudes and in cold weather reduces emissions of carbon monoxide appreciably (DOE 1988b). Methanol is especially attractive for diesel engines because it burns without soot and particulates and emits much less nitrogen oxide, but the use of methanol in diesel engines requires ignition enhancement.

These benefits are not without certain tradeoffs. For example, methanol combustion produces more formaldehyde, a highly reactive carcinogen, than does petroleum product combustion. It is believed that current-generation catalytic systems will be effective in controlling formaldehyde emissions, but further studies are needed (DOE 1988b).

Several states now have alternative fuel programs. The Colorado Air Quality Control Commission has adopted regulations requiring the winter use of oxygenated fuels to reduce ambient levels of carbon monoxide and particulate emissions (DOE 1988b). Legislation requiring future use of methanol is pending in California, and Arizona legislators have introduced bills requiring the use of oxygenated fuels during the winter.

Land- and Water-Resource Conflicts. Energy technologies, whether fossil and nuclear power stations, refineries and synthetic fuel plants, or wind farms and solar electric facilities, can require a good deal of land for diverse purposes such as fuel storage, energy harvesting, and the disposal of residuals. Moreover, some sites are chosen for ease of transportation or power transmission, thus placing them near centers of high population density. Also,

*The August 1988 deadline having passed, EPA must now proceed with implementing the sanctions required by the Clean Air Act; however, the prevalent view seems to be that Congress will somehow have to recognize the great difficulties these areas will face in trying to comply with the NAAQS for O_3 and CO, even with more stringent controls on vehicle emissions.

such facilities are often located adjacent to water bodies to provide cooling water, ready transportation of bulk fuel, or both. Consumptive water use by energy facilities makes a significant demand on water supplies in many regions. The use of land and water for new energy facilities will be in competition with other purposes such as agriculture, recreation, conservation, and homes. The energy industry may, for example, have to give serious consideration to the concepts of remotely located energy parks that serve population centers through new jointly owned and operated transmission grids.

Biomass, the most important component of which is now fuel wood, is highly land intensive. Within the continental United States, land for the large-scale production of biomass for energy may compete for land with food and fiber production and with other uses such as wildlife management, recreation, and watershed protection.. Because food production will continue to use the most fertile soils, biomass energy crops will require fertilization, the runoff from which can place stress on water resources.

In addition, other land- and water-use conflicts arise because fuel exploration and production on some public or native Indian lands and on the outer continental shelf are opposed for ecological reasons. A recent example is the dispute over drilling in the Alaska National Wildlife Refuge. Resolution of resource allocation conflicts is a growing political problem.

NIMBY. Various energy facilities (e.g., nuclear power plants, power lines, and waste disposal facilities) are often considered to be undesirable neighbors. Even when people are convinced that a proposed facility promises a net social benefit, they often don't want it located in their vicinity. This situation often stymies decision making. NIMBY seems to be caused by a deepening loss of trust in institutions associated with energy facility development, which extends from the utilities or other developers to the state and federal regulatory bodies responsible for oversight (Peelle 1988). Public participation in assessment of costs and benefits may offer the best approach to solving this problem.

2.5.1.5 Individual (or family) level consequences of the energy system

Individuals may suffer adverse health or safety consequences of the direct use of energy services in the home, on the job, or during either transportation or recreation. Two seem worthy of some note: indoor air pollution and automobile safety.

Indoor Air Pollution and Safety of Building Energy systems. Indoor air quality is a growing concern and is related to the energy system because changes designed to reduce energy use in existing or new buildings may also adversely affect air quality. Obviously, indoor air quality is determined by the type and quantity of pollutants, the ventilation rate at which air is circulated and treated, and the extent of leakage from the outside (infiltration). Extremely efficient buildings are designed to have very tight shells with low accidental infiltration rates; air quality is maintained by using heat exchangers so that "clean" outside air, brought in to maintain inside air quality, is warmed or cooled by an equal volume of discharged "dirty" air. This system is effective for achieving air quality in very tight buildings. An alternative approach is to control pollutants at the source.

High indoor radon concentrations can be a very serious problem. The radon source is generally the earth surrounding the building foundation, and it will vary enormously with location. The radon infiltration through cracks and joints in the foundation and basement is driven by small pressure differentials between the building and the ground. Effective measures for reducing radon infiltration have been developed (Underground Space Center 1988). Nevertheless, the fear of increasing radon levels has caused some utilities to retreat (in their energy conservation programs) from sanctioning or requiring measures that make buildings very tight.

Kerosene heaters and wood stoves are major sources of pollution, and the resulting air quality problems may be compounded because people using these forms of heating may be inclined to reduce infiltration rates as much as practicable. As mentioned, well-designed equipment, properly vented and designed to achieve complete combustion (e.g., by the use of palladium catalytic surfaces), can minimize the problem.

Undoubtedly, as understanding and monitoring of indoor air quality improve, heating, ventilation, and air conditioning (HVAC) codes and standards will be adjusted, thus, significantly affecting the design and perhaps the energy efficiency of HVAC technology.

The availability of electricity and gas in buildings is a source of accidents of many types. Over the

years, an elaborate system of standards and testing has reduced the risks. Another step in that continuing improvement may be at hand with smart wiring and gas plumbing systems which use diagnostic sensing to evaluate faults in the system or attached equipment and respond intelligently to control energy flow and provide information about trouble.

Automobile Safety. A decade ago, it was argued that reducing automobile size and weight to meet the fuel economy standards then being promulgated might—or might not—have an adverse effect on safety. Occupants of smaller, lighter vehicles, it was thought, would be at greater risk in collisions with heavier vehicles, and smaller vehicles might provide fewer opportunities for impact-absorbing design features. Some automobile safety regulators, on the other hand, argued that better use of available materials and technology (e.g., air bags) could make the more fuel-efficient cars of the mid-1980s safer than the 1977 models (Boehly and Lombardo 1981).

One should also consider different kinds of collisions (e.g., light cars with heavy ones, light cars with light ones, and single-car accidents). In a survey of small-car safety, the General Accounting Office (1982) concluded (1) that smaller cars are not involved in more accidents than large cars, (2) that small-car occupants did suffer greater injuries in collisions with larger vehicles, and (3) that the evidence was inconclusive with respect to collisions between cars of the same size and accidents involving a single vehicle. A great deal still remains to be resolved with respect to these issues. The net long-run effect of fuel economy on automotive safety is a problem that still requires further research.

2.5.2 Energy Insecurity and Fluctuating Oil Prices

In a recent report to the President, DOE comments, "Higher import dependence would increase the risk of major supply disruptions that are damaging to our economic well-being and energy security" (DOE 1987c, p. 7). DOE projects that in the 1990s U.S. annual oil imports may increase from the present level of 12 quads (6 MBD) to the range of 16 to 20 quads (8 to 10 MBD). Furthermore, this may be accompanied by similar increases by other industrialized countries. Imports, however, are not necessarily the best indicator of vulnerability to oil price shocks. Total consumption of oil, regardless of its source, is often a better index of the total costs an economy incurs in responding to sudden increases in oil prices.* Although U.S. oil consumption has been creeping up since 1985, the resultant costs in increased vulnerability need to be balanced against the increases in real GNP that the additional use of oil, a response to lower prices, has made possible.

We are now enjoying what seems to be a period of relative energy stability and security. This stability is manifested in a large gap between world crude production capacity and demand (Fig. 2.6). As discussed, the gap is created by sharply reduced demand resulting from efficiency improvements and fuel switching efforts, primarily by OECD countries, and by increases in stable production capacity, mostly outside the Mideast. Security has also been improved by filling the U.S. Strategic Petroleum Reserve (SPR) to 550 million bbl and by government-owned or controlled reserves of at least that quantity among other OECD countries.

Maintaining this state of relative security requires a comprehensive and flexible policy carefully coordinated with other nations. It should include reliance on free-market prices, which, as noted above, have elicited an enormous conservation response among OECD countries (Figs. 2.2, 2.3, 2.4). It should also include plans for the use of OECD-member strategic reserves under a variety of conditions, possibly including unilateral drawdowns, which could be in the interest of the United States and other OECD countries. Taxes, incentives, standards and other market-compensating tactics may also have a role to play. One objective should be to keep the demand for oil down by encouraging economic efficiency improvements, fuel switching, and the adoption of fuel-flexible technologies. Deregulatory initiatives, particularly in natural gas

*Simulations by a wide variety of models indicate that the loss of real GNP following an oil shock tends to be proportional to a country's total consumption of oil rather than its imports. However, because of differential price level (terms of trade) effects, countries more dependent on imports suffer somewhat greater total economic losses. As much as 70% of the total economic losses caused by a severe oil price shock is represented by the loss of real GNP caused by the temporary unemployment of labor and underutilization of other resources that are involved in adjusting to the new, oil-constrained equilibrium. The remaining 30% reflects a greater claim on domestic GNP by foreigners (resulting from increased oil prices) and a somewhat lower level of GNP at full employment. (See Hickman, et al., 1987.)

and electric power, should also be given serious consideration. R&D can help by (1) enhancing fuel-use flexibility and efficiency, (2) extending domestic oil and gas resources (both conventional and unconventional) and (3) reducing the cost of production. By producing liquids from more abundant fossil fuels (notably coal) and biomass, R&D may produce competitive indigenous liquid fuels in the long run.

Whether or not oil supplies are insecure, we know that prices can fluctuate dramatically as a result of relatively moderate changes in world supply and demand. Large sudden price changes are, of course, economically disruptive and damaging, at least when prices rise. Sudden oil price drops can also be damaging to certain segments of the economy and regions of the country although probably not to the aggregate economy.

Are such large price fluctuations likely to recur? We don't know. In fact, predicting oil prices has proven to be impossible, but Fig. 2.25 indicates some possibilities schematically. We might expect that as conventional oil sources deplete, prices will rise gradually. Obviously, as this trend proceeds, other sources of liquid fuels will eventually compete, including heavy oil, tar sands, shale oil, and liquids from coal. The progress of technology will determine when and at what price.

The market structure (i.e., whether the market is more or less free or is controlled by a cartel) can also influence the price. The shaded area on Fig. 2.25 illustrate this effect. The large fluctuations in price over the past 15 years were not caused by physical depletion, at least not worldwide. Instead, they represent a volatile market, the dynamics of which is not atypical of some commodities. Curlee and Reister (1987) suggest that such fluctuations can occur because short-term elasticities of response to prices are small on both the demand and the supply side of the system, but long-term elasticities are much larger. Under these conditions, small fluctuations in supply or demand can trigger large price responses that do not correct rapidly. Instead, these intermediate-term increases and decreases in price can persist for several years until the long-term reaction compensates. Also, Curlee and Reister observe that intermediate-term fluctuations can be caused by changes from one market structure to another (e.g., by changing from "free" market conditions to cartel control and back again). Such future fluctuations in price are entirely possible. They could be large and could more or less obscure the more gradual price increase caused by depletion.

From the point of view of maintaining a healthy world economy, avoiding large oil price fluctuations is highly desirable. How to achieve greater stability is not obvious, and figuring out practical ways to do it should have a high priority among energy policy makers. The means would seem to be a judicious use of the tools mentioned above, including R&D of the types mentioned. It is not inconceivable that a de facto consortium of oil importing nations (a sort of consumer's cartel) might control its demand such that oil prices remain relatively low for a considerable period of time.

2.5.3 The Needs of Developing Countries

The needs of developing countries are of concern to the United States which is genuinely interested in helping people who are less well off. There are other reasons, too. The North-South poverty gap is a chronic source of tension and political instability. Also, as nations develop, they can become stronger trading partners, which is both an opportunity and a challenge. It is an opportunity for expanding markets for our goods and services, and it is a challenge because newly industrialized countries can be strong competitors.

Development is fueled by modern, more efficient energy sources. The forecasts discussed in Sect. 2.4 concur that the primary energy requirements of the developing world will increase substantially if economic progress is to be achieved. Goldemberg et al. (1988) see efficient use of energy as the least-cost strategy for achieving desired growth, but even in their scenario, the primary energy requirements of the developing nations increase substantially. The increased demand will put an additional stress on world energy sources, particularly oil, and will contribute an increasing fraction of worldwide CO_2 emissions. Accordingly, one challenge for U.S. energy technology R&D policy should be to help develop improved technologies that will promote economic growth in developing countries with the least possible stress on scarce resources and on the environment.

2.5.4 Lack of Public Confidence in Nuclear Power

Nuclear power has long been universally recognized as having the potential for satisfying a major part of the world's requirements for energy. Two central points—the potential for supplying energy on a very large scale and for doing so at prices not very

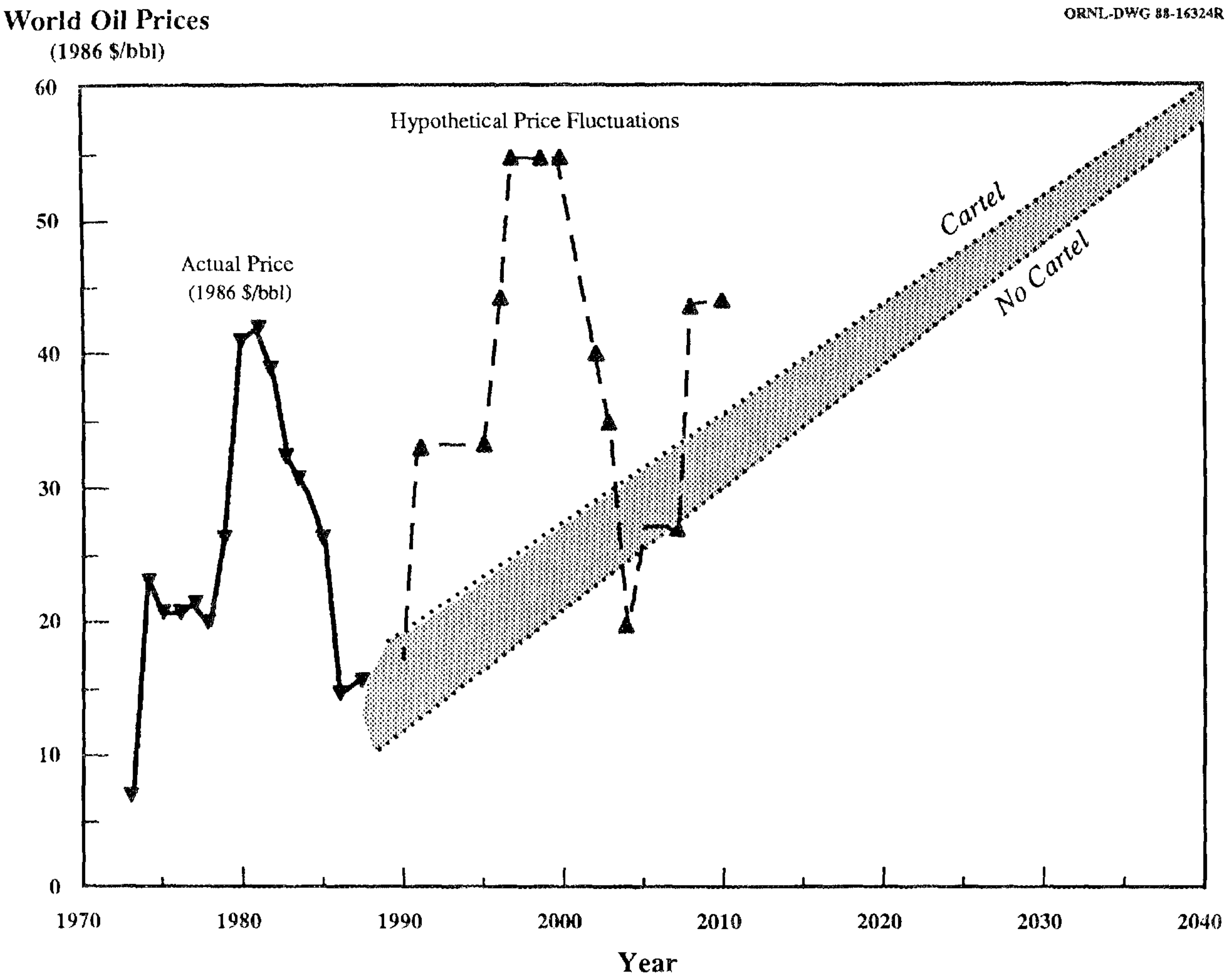

Fig. 2.25. Hypothetical future oil price fluctuations. Fluctuations can be caused by changes in market structure or by small changes in supply. Resource depletion results in a gradual increase in the long-run price. *Source*: Curlee and Reister 1987.

different from contemporary prices for energy from fossil sources—have provided the impetus for four decades of development and implementation of this technology.

However, nuclear power also has two generic characteristics that from the beginning in 1939 [or even earlier, before the actual discovery of fission (Segre 1955)] have been universally recognized as presenting unusual risks to society that would require very careful management if the bright promise of a major new energy source were to be realized. These characteristics—very large quantities of radioactive materials and a potential for the malevolent use of the basic fuel materials, uranium and plutonium—were discussed in Sect. 2.5.1.

We have singled out the problems of nuclear power as one of four problem areas facing the energy system precisely because of this agonizing dilemma. The potential benefits of nuclear power appear to be very great because of the very large scale at which it can be deployed, but the potential risks are perceived by some as too great to permit such large-scale deployment. Yet nuclear power has already become an important contributor to world

energy supply, as well as to that of the United States.* It is important to ensure that all of these reactors continue to operate safely and reliably.

It seems clear that R&D has a major role to play in resolving the important issues surrounding nuclear power, as is discussed in Chaps. 3 and 4. However, improved technologies alone may not be sufficient to restore public confidence. Better institutional arrangements may also be necessary. Rayner and Cantor (1987) suggest three requirements: (1) trust in the institutions managing the technology; (2) agreement about liability for accidents; (3) the consent of those potentially affected by the technology. Inventing the needed institutional arrangements may be as important an R&D objective as improving the technologies themselves.

2.6 CHARACTERISTICS OF A DESIRABLE ENERGY SYSTEM

In this chapter, we have tried to paint a picture of the United States and world energy systems, of how they have evolved and changed, and of the future challenges and problems they may face. We have observed that the systems are remarkably resilient on both the supply and demand side of the economic equation, but the magnitude and speed of the adoption of energy-conservation was generally unanticipated. The improvement in the efficiency of energy use worldwide is certainly a major technological success story of the post-oil-embargo period.

Although significant technological progress has occurred and is occurring with most of the energy sources, no one source is perfect, as we have discussed in this chapter. All have flaws. As is pointed out in the recent report, *The Twenty-First Century Energy Vision* (MITI 1987) the world is entering an era of increasing competition among numerous energy sources and technologies as oil becomes more limited. Despite imperfections in each energy source, the energy system in the aggregate serves us well.

As a whole, the energy system has evolved to exhibit attributes or characteristics that are desired by society. In evaluating R&D needs and opportunities it is important to consider these desirable characteristics. Indeed, R&D should be done to ensure that the energy system will have these characteristics. That was the premise of an earlier ORNL assessment of energy and technology (Livingston et al. 1982).

Table 2.7 lists six of these desirable characteristics: the system should be (1) available, reliable, and resilient (because of diversified sources, flexibility in networks and in the use of energy forms, and adequate reserves to provide security from supply disruptions); (2) enduring (through the use of inexhaustible, renewable, or very abundant sources); (3) inexpensive (to provide cheap energy services for a growing economy in a competitive world); (4) safe (with acceptable impacts on human health and the environment); (5) fair (in that it does not impose inordinate risks or costs on particular individuals, nations, or future generations); and (6) accommodating to cultural needs (such as mobility, convenience, and recreation).

The U.S. energy system displays all these characteristics to one degree or another, but it also has some limitations, as described in Sect. 2.5. Energy technology R&D that could make a difference will be that which contributes significantly to improving energy system characteristics by reducing chronic problems, by providing new opportunities, and by providing insurance against adverse contingencies in an uncertain future. In Chap. 3, promising R&D options are discussed and evaluated in terms of criteria that were chosen by considering these desirable system characteristics and the four problem areas discussed in this chapter. The correspondence between the desirable characteristics of the energy system as a whole and the criteria used in Chap. 3 to evaluate specific R&D options and areas is indicated in Table 2.7.

*Nuclear power now contributes 5% of the world energy supply, compared with 7% for hydropower. In the OECD countries, nuclear power exceeds hydropower. It contributes a much larger share of electricity generation than of total energy supply, especially in certain countries: nearly one-fifth of all electricity in the United States (more than oil and gas combined), about one-fourth in Japan, and more than two-thirds in France.

Table 2.7. Correspondence between desirable energy system characteristics and criteria used in Chap. 3 to evaluate energy technology R&D options and areas

Characteristics of a desirable energy system	Criteria used to evaluate energy technology R&D in Chapter 3
1. Energy sources available, reliable, and resilient — diversified — flexible — secure reserves — geographically distributed (i.e., available everywhere)	1. Energy significance — near term — longer term — indefinite future
2. Enduring (inexhaustible and/or renewable and sustainable) — primary resources adequate for the long term — low use of critical materials	2. Energy security — reduces oil use — facilitates shift to sources other than oil or gas
3. Inexpensive and prices stable — compatible with economic goals — competitive in world markets — total energy costs a small fraction of Gross National Product	3. Economics and international competitiveness — cost competitive — certainty about costs — contributes to exports — leads to spinoffs
4. Environmentally acceptable and safe — little discharge of hazardous materials — small probability of serious accidents — low impact on local and regional environments — small impact on the global commons resources such as atmosphere and the ocean	4. Environmental, health, and safety impacts — free of major problems such as accidents — would reduce CO_2 emissions — few routine but damaging impacts
5. Fair — to individuals, communities and regions — to other nations — to future generations	5. Social impacts — infrastructure organized for deployment — accepted by public — free of high risk
6. Accomodates cultural needs — mobility — covenience — recreation	6. Beneficial to less-developed countries

Chapter 3
The R&D Options

There is a vast array of technologies under development that, if successful, would be beneficial in producing energy or improving its use. It is the intent of this report to identify those technologies that are likely to be particularly useful over the next 50 years (i.e., those technologies which should be the core of an R&D program aimed at ensuring that energy will not be a major constraint on society's goals).

As explained in Chap. 2, there is no perfect energy technology. Everything in use now or under development has some serious liabilities. Each technology may have a limited resource base (e.g., oil and natural gas), cause significant environmental damage (coal), pose safety concerns (nuclear), or be very expensive (solar) or require action by many people to be implemented widely (efficiency improvements).

The technologies discussed in this chapter have been identified as the best compromises to contribute to the goals discussed in the previous chapter. Sixteen criteria in six categories were applied as listed in Table 3.1. The criteria were developed from a review of energy problems and issues—in particular, factors contributing to desirable characteristics of the energy system which influence how it will be able to meet society's needs, as discussed in Chap. 2 (Sect 2.6). In general, the criteria emphasize the magnitude of the potential energy contribution of the technology (or technological group) assuming successful R&D and implementation, the economic advantage that may accrue, the effect on national energy security, and the environmental, social, and international impacts it may have.

The first step in this bottom-up review was to organize teams of ORNL staff members to review 13 areas of energy technology covering end-use sectors and the various sources and 8 areas of crosscutting science and technology. Each team was asked to review the research programs at ORNL, other national laboratories, and other research centers. The teams relied heavily on the research plans of DOE, the Electric Power Research Institute (EPRI), and the Gas Research Institute. Each team prepared a report to summarize R&D opportunities in its area; these reports are collected in the three parts of Vol. 2 of this report. After reviewing the team reports, the synthesis team prepared the lists of R&D opportunities that comprise Appendices A and B of this report. These lists are not exhaustive of all energy R&D programs. Rather, they represent the reviewer's selection of R&D opportunities that have significant potential for improving existing technology or creating new ones.

Fifty technologies or technological areas were selected as having the greatest promise and are listed in Table 3.2. This list was prepared by comparing all the technological groups listed in Appendix A to the 16 criteria in Table 3.1. When several competing technologies were included in the group, the best results were noted. The detailed evaluations of the options are discussed in Vol. 2. The selections in Table 3.2 were made on the basis of judgments of the overall pattern of the ratings for the 16 criteria. Where directly competing technologies are approximately equal in promise, they are aggregated in the table and identified in the discussion below. Table 3.3 shows the evaluation under the criteria for the 50 options.

Most of the 16 criteria defined in Table 3.1 are straightforward. A few words of explanation may be helpful, however, with respect to the first three criteria, which relate to energy significance.

We considered three time frames: near-term (by the year 2000), longer-term (by the year 2040), and ultimate significance. For each option in each time frame, we assigned a rating (H for high significance, M for medium, and L for low) with numerical guidelines.

We created the third time frame (ultimate significance) for the large or inexhaustible energy sources (coal, breeder reactors, and solar and fusion

Table 3.1. Criteria for selecting top R&D opportunities

Energy significance

1. Does this technology have the potential for making a major near-term (by the year 2000) contribution to our energy system (assuming the economics prove reasonable)?
   - H 1 quad/year equivalent
   - M at least 0.2 quad/year
   - L <0.2 quad/year

2. Does this technology have the potential for making a major longer-term (by 2040) contribution?
   - H 4 quads/year equivalent
   - M 1 quad/year
   - L <1 quad/year

3. Can the technology continue to grow indefinitely beyond the 50-year time frame, or is it resource or application constrained?
   - H virtually inexhaustible and unconstrained
   - L significant limitations

Economics and international competitiveness

4. Is the technology likely to be cost competitive with other means of satisfying the energy requirements?
   - \+ likely to be competitive even at low energy prices
   - 0 competitive with modest price rise (i.e., oil at $20-35/bbl)
   - \- competitive only with expensive energy (i.e., oil over $35)

5. Is the technology understood well enough at this time that the cost projections assumed in question 4 can be considered accurate?
   - \+ cost projections should be accurate; few if any hidden surprises
   - 0 about the same as most R&D options
   - \- many uncertainties

6. Will this technology generate significant exports of equipment, services, or resources?
   - ++ large potential market
   - \+ some market, but not great
   - 0 negligible

7. Is development likely to lead to other valuable technologies?
   - \+ significant potential
   - 0 little potential

Environmental, health, and safety impacts

8. Is the technology likely to be free of major problems such as large quantities of toxic materials or catastrophic accidents?
   - \+ little risk, or much less likely than current equivalents
   - 0 about the same as current equivalents
   - \- some major uncertainties

Table 3.1 *(continued)*

Environmental, health, and safety impacts (continued)	
9. Would deployment of this technology result in reduced emissions of carbon dioxide?	
+	significantly less CO_2 likely to be released
0	not much difference, or depends on what it replaces
-	likely to produce more
10. Would manufacture and use of this technology result in relatively few routine but damaging environmental and occupational impacts?	
+	little potential for problems
0	regular monitoring and corrections required
Energy security	
11. Could this technology reduce oil imports?	
++	yes, by at least 200,000 bbl/day (0.4 quad/year) by the year 2000
+	some, but less than that
0	little or none, maybe even negative
12. Could this technology facilitate shifts to other fuels in case of shortages of oil or natural gas?	
+	easy to shift fuels, at least 200,000 bbl/day within 1 year
0	some, but less than that
-	may make the system less flexible
Social impacts	
13. Is the existing industrial/commercial infrastructure well organized to deploy this technology?	
+	can be easily accommodated
0	moderate changes to institutions required
-	major changes required
14. Is the technology likely to be readily accepted by the public?	
+	likely to be popular
0	generally acceptable or no impact on the public
-	likely to be controversial
15. Will this technology be free of concerns (e.g., significant accidents or cost overruns) that could make it appear to be a high-risk investment?	
+	few if any problems anticipated
0	some problems, but should be manageable
-	major uncertainties
Less-developed country impacts	
16. Will this technology be directly beneficial to economically underdeveloped countries?	
+	will be quite useful
0	few or no advantages

Table 3.2. Promising energy technology R&D options

Transportation

Advanced engine technologies
Continuously variable transmission
Improved aircraft efficiency
Automated dynamic traffic control

Buildings

Heat pumps
Lighting
Smart control systems
Envelopes
Manufactured buildings and components
Computer-assisted design
Retrofits of existing buildings

Industrial

Catalysts
Sensors and controls
Separations
Advanced heat management
Cogeneration
Pulp and paper processes
Steel processes
Agricultural techniques

Electricity

Superconductivity applications
Power electronics

Advanced conversion to electricity

Aeroderived gas turbines
Brayton cycle
Kalina cycle
Fuel cells
Hot gas cleanup

Storage

Advanced batteries
Thermal storage

Petroleum

Enhanced oil recovery
Field characterization techniques

Natural gas

Exploration and drilling techniques
Unconventional gas techniques

Coal

Oil substitutes
Fluidized bed combustion
Bioprocessing
Gasification
Liquefaction

Nuclear power

Improving existing LWR technology
Modular high-temperature gas reactor
Liquid metal fast breeder reactor
Waste management techniques

Fusion

Reactor systems
Fissile fuel breeder

Biomass

Feedstock development
Conversion technology
Municipal solid waste processing

Solar electric

Photovoltaic energy conversion
Solar thermal
Hydroelectric
Wind turbines

Table 3.3. Evaluation of promising R&D options

Technological opportunities	Energy significance			Economics/competitiveness				Environment			Security		Social do-ability			
	Near term	Long term	Ultim. poten.	Energy costs	Cost uncert.	Export equip.	Spin offs	Severe impact	CO_2	Other	Oil imp.	Fuel flex.	Infra struc.	Public percep.	Invest. risk	LDC impact
Transportation																
Advanced engine technologies	M	H	L	0	0	0	0	0	+	+	++	+	+	0	+	+
Continuously variable transmission	M	M	L	0	+	0	0	0	+	+	++	0	+	0	+	+
Improved aircraft efficiency	M	M	L	+	+	++	0	0	+	+	++	0	+	0	+	+
Automated dynamic traffic control	L	M	L	+	0	+	0	0	+	+	+	0	0	+	+	+
Buildings																
Heat pumps	M	H	L	+	0	++	+	+	+	+	+	0	+	+	+	+
Lighting	M	M	L	+	0	++	+	+	+	+	+	0	+	+	+	+
Smart control systems	M	H	L	+	+	++	0	+	+	+	+	+	+	+	+	+
Envelopes	M	H	L	+	0	++	0	+	+	+	+	0	0	+	+	+
Manufactured buildings and components	L	M	L	+	0	++	0	+	+	+	+	+	0	+	0	+
Computer-assisted design	L	M	L	+	0	++	0	+	+	+	+	0	+	+	+	+
Existing building retrofits	H	H	L	+	+	0	0	+	+	−	+	0	+	+	+	+
Industrial																
Catalysts	M	M	L	+	+	++	0	0	+	+	+	0	+	+	0	0
Sensors and controls	H	H	L	+	+	+	0	0	+	+	+	0	+	0	+	0
Separations	M	M	L	0	+	++	+	0	+	+	+	0	+	0	+	0
Advanced heat management	H	H	L	+	0	++	0	0	+	+	+	0	+	0	+	+
Cogeneration	H	M	L	+	0	+	0	0	+	+	+	+	+	+	+	+
Pulp and paper processes	M	M	L	+	+	++	0	+	+	+	+	+	0	0	0	0
Steel processes	M	L	L	+	+	+	0	+	+	+	0	0	+	0	+	+
Agricultural techniques	M	M	L	+	0	+	0	0	+	0	+	0	+	0	0	+
Electricity																
Superconductivity applications	L	M	L	−	−	++	0	0	+	+	0	0	0	+	−	0
Power electronics	M	M	L	+	0	++	0	0	+	−	+	0	+	0	+	0
Advanced conversion																
Aeroderived gas turbines	M	H	H	+	0	++	0	0	+	+	+	+	+	0	+	+
Brayton cycle	L	H	H	+	0	++	0	0	+	+	+	0	+	0	+	+
Kalina cycle	L	M	H	0	0	++	0	0	+	+	+	+	+	0	+	+
Fuel cells	M	M	H	0	−	++	+	+	+	+	+	0	0	+	0	+
Hot gas cleanup	L	H	H	0	−	++	+	0	+	0	0	0	+	0	+	+
Storage																
Advanced batteries	L	M	H	−	−	+	0	0	+	+	+	0	−	0	−	0
Thermal storage	L	M	H	0	0	0	+	+	+	+	+	0	0	0	+	+
Petroleum																
Enhanced oil recovery	H	M	L	0	+	+	0	0	0	0	++	0	+	0	0	0
Field characterization techniques	H	M	L	0	+	+	0	0	0	0	++	0	+	0	0	0

Table 3.3. (*continued*)

Technological opportunities	Energy significance			Economics/competitiveness				Environment			Security		Social do-ability			
	Near term	Long term	Ultim. poten.	Energy costs	Cost uncert.	Export equip.	Spin offs	Severe impact	CO_2	Other	Oil imp.	Fuel flex.	Infra struc.	Public percep.	Invest. risk	LDC impact
Natural gas																
Exploration and drilling techniques	H	M	L	0	+	+	0	0	0	+	++	0	+	0	0	0
Unconventional gas techniques	H	H	L	0	+	+	0	0	0	+	++	0	+	0	0	0
Coal																
Oil substitutes	M	M	L	+	+	++	+	0	−	0	+	+	+	0	+	+
Fluidized-bed combustion	M	H	H	+	0	++	+	0	−	+	+	0	+	0	+	+
Bioprocessing	L	M	H	−	−	++	+	0	−	+	+	0	0	0	0	+
Gasification	M	H	H	0	0	++	0	0	−	−	+	0	0	−	0	+
Liquefaction	L	H	H	−	0	++	0	−	−	0	++	0	0	−	−	0
Nuclear power																
Improving existing LWR technology	H	H	L	+	+	+	+	+	+	+	+	0	+	0	0	0
Modular high-temperature gas-cooled reactor	L	H	L	+	0	++	+	+	+	0	+	0	+	0	0	+
Liquid metal fast breeder reactor	L	M	H	−	0	++	+	−	+	0	0	0	0	−	−	0
Waste management techniques	L	H	H	+	+	0	0	+	+	+	0	0	−	0	0	0
Fusion																
Reactor systems	L	L	H	0	0	0	+	+	+	0	0	0	0	+	−	0
Fissile fuel breeder	L	L	H	0	0	0	+	+	+	0	0	0	0	0	−	0
Biomass																
Feedstock development	M	H	L	0	0	+	+	+	+	−	++	0	−	0	+	+
Conversion	M	H	L	0	0	+	+	+	+	−	++	0	−	0	+	+
Municipal solid waste processing	M	M	L	+	+	0	0	0	0	−	0	0	0	−	0	0
Solar electric																
Photovoltaic energy conversion	L	M	H	−	−	++	+	+	+	0	+	0	0	+	+	+
Solar thermal	L	M	H	−	−	++	0	+	+	+	+	0	0	+	+	+
Hydroelectric	M	M	L	0	+	0	+	+	+	0	+	0	−	−	0	+
Wind turbines	L	M	L	0	0	++	0	+	+	0	+	0	0	0	+	+

energy). We struggled with the issue of whether or not an end-use technology can be inexhaustible. Is efficiency an exhaustible resource? For example, compared with the current fleet average, the improved mileage of a 50-mile/gal (MPG) car would incur a large energy savings that would last forever. But can the energy savings grow? The energy savings realized by replacing 10-MPG cars with 20-MPG cars is larger than the savings gained by replacing 25-MPG cars with 50-MPG cars (both changes are by a factor of two, but the base consumption is lower for the second case).

We decided that efficiency is an exhaustible resource. Thus, all the technological options to improve end-use efficiency were given a score of L (significant limitations) for ultimate potential. On the supply side, we decided that the ultimate potential of hydroelectricity and biomass is significantly limited.

To estimate energy significance, we estimated the potential market for each option and the guessed market penetration. In general, we assumed that future markets would be about the same size as current markets.

We adopted two different methods for defining the magnitude of the energy associated with an option. For end-use options, we estimated energy savings. For energy conversion, storage, and supply options, we estimated the magnitude of the total installed capacity.

The evaluations leading to the results listed in Table 3.3 were performed in meetings between each technology area team and the synthesis team. The meetings began with reviews of the options listed in Appendix A. To introduce the criteria in Table 3.1, a few options (or an aggregate option) were evaluated in the meeting. For example, consider steel, for which seven technological options are listed in Appendix A. In the meeting, an evaluation was performed for the aggregation of the seven options. Later, in a smaller meeting, an evaluation was performed for each of the seven options. After all the aggregate analyses had been completed, the technology team and the synthesis team chose the aggregated options with the greatest promise, listed in Table 3.2. The technologies in Table 3.2 were selected on the basis of the overall pattern of the ratings for the 16 criteria.

The criteria provided a basis for systematically reviewing each option. Great care was taken to ensure that the criteria were consistently applied and that the options selected represented the most attractive compromises based on the results. No quantitative weighting methodology was used. As discussed in Chap. 2, no one knows just what our energy requirements will be in the future, so various perceptions of energy needs lead to different R&D programs to meet the needs. In addition, R&D programs are inherently unpredictable, and observers do not necessarily share the same expectations of success. Therefore, there is no completely objective way to rigorously compare different types of programs, and it should be noted that the list is, by its nature, somewhat subjective. A different group of analysts using the same methodology would have produced a different list, (although there almost certainly would be a substantial overlap). However, these results have been widely reviewed, and major differences of opinion have led to appropriate revisions in the list.

Thus, there have been three levels of evaluation: first, the review by the researchers involved leading to the lists in Appendix A; second, the comparison to the energy, economic, environmental, and social criteria; and third, the review by the researchers and other observers of the results. In addition, these options are viewed in Chap. 4 from a broad energy perspective to see how they fit into a balanced R&D strategy.

It should be noted that exclusion from Table 3.2 does not suggest that a technology is not worth pursuing. On the contrary, all the technologies considered (and discussed in Vol. 2) have merit. For example, some technologies were excluded because their energy contribution would be small, but they might still show a high benefit-to-cost ratio. In other cases, the technology itself is likely to be important, but the improvements due to the R&D will not add materially to this success. The purpose of this list is to focus attention on the key energy R&D opportunities that are most likely to make a significant difference in our energy system over the next 50 years.

In light of these caveats, a brief justification of the selection is in order and is given below in Sects. 3.1.1 and 3.1.2. Further details about these and other technologies can be found in Vol. 2.

R&D options in crosscutting technologies and areas of science (Appendix B) may be indirectly important to the success of one or more of the energy technology R&D options. For instance, advanced materials are key to high-temperature turbines, very efficient automobile engines, and various coal conversion processes. These crosscutting

technologies are listed in Table 3.4 and discussed in this chapter (Sect. 3.2), but no effort was made to analyze their desirability as was done for the energy technology R&D options.

3.1 PROMISING ENERGY TECHNOLOGY R&D OPTIONS

3.1.1 Energy End-Use Technology

3.1.1.1 Transportation

Automobiles, light trucks, and airplanes have all been made remarkably more efficient over the past 15 years. The technology exists for substantial further improvements, but most are unlikely to be implemented at current fuel prices. The goal of the R&D program is to provide economically attractive new technology.

Because transportation accounts for the consumption of vast amounts of oil and because of the difficulty of converting to other fuels, research must be directed at both efficiency and fuel switching. Electric vehicles would appear to provide a means to accomplish fuel switching, but their performance has been inadequate; internal combustion engines have been improved faster. Electric vehicles are discussed in Sect. 3.1.1.6 (Storage) because batteries are the major technological constraint.

Eventually, alternative fuels will have to be used for transportation to reduce or eliminate dependence on gasoline. Alcohols from biomass, liquids from coal, and hydrogen have been proposed for use in automobiles. The major constraint to the use of these fuels for the next several decades is likely to be their cost. Earlier penetration of methanol and other oxygenated fuels could occur for environmental reasons; they result in less ozone (a prime cause of smog) and less carbon monoxide than does gasoline [see Transportation (Sect. 1.1 in Vol. 2) and Sect. 2.5.1.3]. Automobile engines can be readily adapted to methanol using available technology, so they are not included on the list of most promising technology developments. However, research on the integration of the issues of fuel supply (production and distribution) and engine fuel requirements may point the way to productive lines of development.

Research on automobile and truck efficiency covers improved engines, more efficient drive trains, and factors such as aerodynamics and weight that affect mileage. Promising ***advanced engine technologies*** under development include the gas turbine and various low-heat-rejection engines. The gas turbine promises high-efficiency with expectations for low emissions (as yet undemonstrated) and multifuel capability, but it will require ceramic components which can operate reliably at very high temperatures. The DOE target is 2500°F (1371°C). A silicon-carbide turbine rotor has now been successfully demonstrated in a test-bed engine at 2200°F (1204°C) (DOE 1988c). Final questions regarding emissions must be addressed when prototype engines are available.

Low-heat-rejection (LHR) reciprocating engines offer improved efficiency through minimization of heat losses and reduction of the parasitic losses of fans and water pumps. Reduction in size or elimination of radiators can permit additional improvement in vehicle aerodynamics as well. High-temperature materials, thermal barriers, and compatible high-temperature lubrication systems are the critical requirements for LHR engines. In addition, combustion systems must be optimized and, if necessary, reconfigured for LHR engines to ensure compliance with emissions regulations.

Turbocompounding and bottoming cycles are demonstrated fuel-saving technologies and are very effective when married with LHR engines, but they are more practical for heavy trucks than for light trucks and passenger cars.

With continued progress in combustion control and enhancement (e.g., catalytic surfaces), unthrottled engines, with their inherent efficiency advantage, may achieve larger penetration into the transportation sector. Spark-ignited (or other ignition-enhancing technology) versions of unthrottled engines will have the fuel flexibility to use gasolines and methanol instead of only diesel fuel. Direct injection versions of these engines are typically the most efficient, thus falling under the definition of the widely recognized DISC (direct injection stratified charge) engine. Application of LHR technology to spark-ignited, unthrottled engines may have noteworthy potential and as yet is relatively unexplored. Two-stroke (or even rotary) versions of these engines, which offer better power-to-weight ratios and lower internal friction losses than the more common four-stroke versions, may yield additional fuel economy gains, but again combustion enhancement (with consideration of fuel flexibility) and emission control will be the keys to the success of these technologies.

The ***continuously variable transmission*** (CVT) introduces an essentially infinite number of gears,

Table 3.4. Crosscutting technologies and related areas of science

Microelectronics and sensors

Smart systems for control of industrial processes, combustion efficiency, building heating/cooling/lighting, etc.
Sensors for determining conditions in harsh environments

Advanced materials

Ceramics for high-temperature engines
Surface treatments, including low-friction materials
Superconductors
Materials by design
Lightweight structural materials
High-temperature, erosion- and corrosion-resistant materials for hot gas cleanup, turbines, heat exchangers, etc., in harsh environments.

Biotechnology

Improved plants for high-productivity biomass
Microbes for coal cleaning, oil recovery, and hydrogen production
Enzymes

Separations

Improved distillation
Membranes
Supercritical fluid extraction
Low-grade ore recovery, including recovery from seawater

Combustion science

Efficiency improvement and environmental control of internal combustion engines and boilers
Enhanced fuel-switching capability
Municipal waste incineration

Geosciences

Improved understanding of reservoirs for enhanced oil recovery
Gas exploration techniques
Unconventional methods of gas recovery
Geothermal energy
Waste sequestering

Effluent management

Waste reduction and recycling
Pollution control techniques that improve the efficiency of chemical and physical processes for transforming and scavenging harmful effluents
Solid waste disposal

Decision making and management

Implementing high-energy-efficiency strategies
Planning for energy technologies involving social risk
Managing a reduction in the emissions of carbon dioxide
Utility least-cost planning
Planning for uncertainties

allowing an engine to remain constantly at its most efficient speed; but material and reliability problems must be solved before CVT will be practical for any but small vehicles. Further gains could be realized by designing the engine to operate at precisely the most efficient speed, since the need to design for a range of speeds imposes compromises on other factors, including economy. Alternatively, computer-optimized control of the engine and transmission coupling with current automatic transmissions may prove to be a more practical way to achieve similar objectives. Lighter materials, improved aerodynamics, and tires with lower rolling resistance, as well as a multitude of specific design innovations, may be important in improving vehicle mileage.

Improved aircraft efficiency will not save as much energy as automobile efficiency is expected to save because the current fuel requirements are so much lower (although air traffic is increasing rapidly). Nevertheless, substantial gains are possible, and advanced materials are a major target. Composites, plastics, and light alloys may all simplify manufacture while saving weight. Advanced aerodynamics can reduce drag significantly, and improved engines (such as ultra-high-bypass jets and high-speed turboprop engines) should be more economical. Also, improvements in operations—including flight planning, load management, and air traffic control—may offset the effects of increased congestion. All these gains are likely to be effective in reducing demand for petroleum, as fuel is a major expense of airlines. Reductions in fuel use by as much as 35 to 40% per passenger mile seem likely over the next decade or two (Vol. 2, Sect. 1.1). Aircraft are a major export item, so improved planes and associated technology would help keep a competitive advantage.

Automated dynamic traffic control is a system that monitors traffic patterns and adjusts flow. Energy savings are not the primary goal of this research program, but idling or slowly moving automobiles waste considerable fuel. Research concentrates mostly on software development to handle the data and calculations and on hardware development to improve the reliability of the sensors and controls.

3.1.1.2 Buildings

Energy use in residential and commercial buildings increased from 33% of all U.S. energy consumption in 1972 to 36% in 1987. Most energy is used for space heating and cooling, hot water, and lighting. Improvements can be made to the equipment that actually consumes this energy and to buildings themselves.

Many opportunities exist for improved energy efficiency in new and existing buildings with existing technology; these measures are not being implemented at a rate commensurate with their cost effectiveness, even though they can pay high dividends for both energy efficiency and economics. However, the research involved is institutional and behavioral rather than physical, as discussed in the section on decision making under Crosscutting Technologies in this chapter and in Chap. 4, Sects. 4.1 and 4.2.

Heating and cooling of buildings account for about one-half of all the energy used in the building sector. Some modern furnaces are virtually as efficient as they can ever be (condensing furnaces with 92% efficiency are commercially available), but major gains in efficiency are still possible with advanced ***heat pumps***. The coefficient of performance of heat pumps and air conditioners theoretically could be more than doubled. Development is under way on capacity modulating systems, improved controls, new refrigerants, and new cycles.

In addition to improved electric heat pumps, thermally activated heat pumps (TAHP) are being developed. These can be gas-fired absorption units (which are available now in large, commercial sizes but will require improvement before they are widely popular) or more conventional vapor-cycle units with the electric motors replaced with, perhaps, Stirling engines. Such units could be fired by a variety of fuels or even solar collectors and would allow the use of waste heat for high efficiency. Before advanced TAHPs become practical, considerable work is required for engine longevity or absorption component durability, as well as improved costs and performance. Current R&D results are promising.

More efficient heat pumps would not only save energy themselves, but their range of competitiveness with oil and gas furnaces would be extended. Because very efficient heat pumps (either TAHP or electric) can deliver more energy than they consume, the overall energy savings could be substantial. They should find ready acceptance among consumers and could be major export items. However, new chemical compounds must be developed to replace Freon and other refrigerants containing chlorofluorocarbons (CFCs). Thus, R&D will be required just to keep heat pumps at their present efficiency.

Improved ***lighting*** technologies also could save considerable energy, perhaps 2 quads/year overall and maybe more with advanced daylighting techniques. Fluorescent lamps are particularly appropriate for improvements, even though they are already much more efficient than incandescent lamps. Reduced self-absorption, more efficient phosphors, and higher ballast frequencies are possible advances. Improved fluorescent lamps are likely to replace some incandescents, with notable energy savings.

Buildings will increasingly incorporate ***smart control systems*** based on microelectronics and sensors to determine the need for space conditioning and lighting (including daylighting) and to supply precisely the right amount of service, avoiding the waste of overdesign in present systems. Although smart systems exist, R&D is required to improve systems and apply them to residential as well as commercial situations. Further development of both the electronics and the sensors is required to achieve the potential savings.

Heat losses through building ***envelopes*** can be sharply reduced with advanced materials. A prime focus is on the development of materials similar to existing products but with higher thermal resistance. For instance, high R-value composite walls and foam cores could sharply reduce construction costs as well as energy requirements. The pending ban on CFCs, a prime component of most of the present foams, suggests that substitutes such as evacuated panels should be developed to avoid a drop in the efficiency of new buildings. Active systems are another possibility. For instance, windows with switchable emissivity (opaque on winter nights, transparent during the day) could produce major savings.

Building construction practices are rapidly shifting toward ***manufactured buildings and components***, providing an opportunity for new materials and innovative design as well as economic gains in an industry that has been fragmented and slow to introduce improvements. However, the techniques and specific requirements of off-site construction are not yet mature, and research is required to ensure that the end products will be acceptable to buyers.

Computer-assisted design techniques are being developed to optimize building performance for any specific application. As the appropriate software is developed, a great deal of routine design work can be relegated to the computer, with focus on attributes such as energy efficiency, safety, and security. Energy requirements can be minimized through better prediction of building performance for a specific site and through selecting the best possible envelope and equipment. It can improve the economic application of passive (or even active) solar design features. Such techniques also go hand in hand with custom manufactured buildings and components.

Efficiency is easiest to incorporate into buildings when they are designed and constructed. However, ***retrofits for existing buildings*** can significantly reduce energy consumption. Many efficiency improvements are already available (e.g., insulation, efficient appliances and lighting). However, recent studies have shown that performance often fails to reach pre-investment estimates. The major research areas concern methodology for providing reliable data on the benefits from efficiency retrofits, and measurement and analysis of the influence of human and other factors on the effectiveness of retrofits.

3.1.1.3 Industry

Industry uses approximately 36% of all U.S. primary energy. Its efficiency has improved greatly since 1972, when the industrial share of energy use was 42%. Perhaps more than in the other sectors, industry's decisions on investments to conserve energy are based on economic analysis, though other considerations also play important roles. Because of the wide variety of ways that industry uses energy, many different options will be required to facilitate further gains in efficiency.

Catalysts are used in many industries and in consumer products including automobiles (which use catalytic converters) to facilitate chemical reactions. The chemical and refining industries are particularly heavy users, and many opportunities exist for reducing energy requirements by the use of better catalysts. Better understanding by the scientific community of basic mechanisms may lead to new classes of catalysts. Important possibilities are applications to one-step conversion of methane to methanol, photocatalytic reduction of water, combustion enhancement, and pollution control.

Sensors and controls also have widespread potential for improving efficiency. Almost any process that uses energy can be made more efficient if adequate information is available to optimize the specific conditions at each point in the process. Sensors measure many different parameters (e.g., temperature, pressure, concentrations) in a variety of environments. Thus, each process may call for many different specifically designed sensors and a

complex control system that may also handle other functions such as quality control and equipment maintenance scheduling. R&D is required to devise sensors that can withstand harsh environments and to devise new ways of processing information.

One of the most energy-intensive processes is the ***separation*** of two or more components in a mixture, such as through distillation. Separations account for about 20% of all industrial energy use, so improvements can have a significant benefit for both energy and economics. Distillation will always be energy intensive, but research on the basic process is surprisingly meager, suggesting that improvements in design are possible and that new column-packing materials are potentially advantageous. Larger energy savings are probably available from replacing distillation with other processes, including use of membranes (e.g., reverse osmosis, microfiltration) and supercritical fluid extraction. Both are in use now, but there is considerable potential for improvement.

The amount of waste heat produced by the industrial sector can be reduced by ***advanced heat management***. The principal advance is improved monitoring and control of all the operations in a plant to optimize conversion and distribution of energy. Wherever possible, waste heat from a high-temperature process provides the input energy for a lower-temperature process. Analysis based on the second law of thermodynamics can identify waste heat recovery opportunities (see the discussion of the Pinch Technology design method in the Industrial chapter of Vol. 2, Sect. 1.3.2.1.5).

R&D needs include both software and hardware. Computer software can be used to design plants and to monitor operations. Examples of improved hardware are cost-effective heat exchangers, high-temperature heat pumps, high-temperature recuperators, and thermal storage units for recovery of high-temperature reject heat.

Cogeneration is the simultaneous production of electric power and process heat or process steam. A favorable regulatory climate [the Public Utility Regulatory Policies Act of 1978 (PURPA)] has encouraged substantial growth in cogeneration in both the industrial and the buildings sector. In the industrial sector, the primary R&D goal is to develop small- to medium-size systems that have a flexible electricity-to-heat ratio.

Two of the advanced conversion technologies in Table 3.2 (and discussed in Sect. 3.1.1.5), the aeroderived gas turbine and some types of fuel cells, may be attractive machines for cogeneration. In particular, the intercooled steam-injected gas turbine (ISTIG) can accomodate variable amounts of steam returned to the turbine combustor, and hence it has a flexible electricity-to-heat ratio. Steam not returned to the turbine is used for process heat. The ratio of electricity to process steam output can be varied considerably. Cogeneration using ISTIG with biomass gasification for fuel could be an attractive technology for some developing nations.

For cogeneration applied to buildings, a primary goal for R&D is to produce a cost-effective heat-driven absorption chiller or heat-engine-driven chiller that can be integrated into a cogeneration system to provide cooling as well as heating and electricity. Small gas turbines incorporating advanced ceramic rotors are a promising driver for such a system.

The five promising energy technology R&D options discussed in the preceding paragraphs all have applications in several different industries, and some have applications in the buildings sector. They may all be important and economic energy savers, and they are likely to provide export business. Further, they should provide environmental benefits by improving energy efficiency and be relatively easy to implement.

Several additional developments could make a major difference in specific industries; the paragraphs that follow provide examples of promising opportunities for improving energy efficiency.

In the paper industry, the energy-intensive steps are the ***pulp and paper processes***. Chemical pulping is dominated by the kraft process. Because the kraft process is mature, efficiency improvements from many incremental changes will probably increase the energy efficiency by less than 25% in the next 50 years. The energy required to recycle paper is approximately one-half the amount required for the kraft process. A primary R&D need is a better process to remove ink and fillers from the recycled paper. In the papermaking process, improved process control (better automation), process physics (higher speeds), and improved materials (higher-pressure rollers) are called for. The three most promising advanced processes (biopulping, chemical pulping with fermentation, and ethanol organosol pulping) involve integration of at least one fermentation process with a conventional pulping process.

In the next 50 years, electronic media could displace paper in many applications. Although the current consumption of paper is increased by

computer use, the development of cheap, highly reliable digital storage technology (floppy disks and optical disks) could cause fundamental changes. The electronic storage media are two to seven orders of magnitude less expensive and more compact than paper and may have better archival capabilities.

Advanced processes in ***the steel industry*** include ore-to-powder steelmaking and direct reduction ironmaking. Both could revolutionize the industry as well as provide energy savings benefits of over 40%. The total energy required to produce steel from scrap is less than one-half the energy required to produce steel from raw materials. However, scrap contains trace elements that can have adverse effects on the properties of steel. Improved processes for scrap beneficiation could result in substantial energy savings. Continuous casting results in a large productivity gain over the traditional ingot casting. The current refractory materials that are used as spouts to pour the steel must be replaced frequently, and the debris from the spouts contaminates the steel. Advanced refractories could result in a substantial improvement in the continuous casting process.

Agriculture provides several attractive opportunities for improved energy use efficiency. The improved technologies are not driven by energy considerations, but increased energy efficiency is an important side benefit. Crop yields will continue to increase, plant varieties that reduce losses due to stresses (such as pests and drought) will be developed, and fertilizer and water use efficiency will increase. Grain crops that fix their own nitrogen as legumes do will be developed. Biotechnology will aid in the development of these improved plants.

Sensors, control systems, and information systems will be developed that will

- improve energy efficiency for machinery field operations by limiting machinery to specified tracts in fields (thus reducing soil compaction, which reduces crop yields);
- allow for variable rates of fertilizers to be applied within a field (thus optimizing fertilizer use); and
- improve the timing and optimize the quantity of irrigation.

Advances will continue to be made in reduced tillage operations. If livestock feed-use efficiency is improved, the amount of feed required will be reduced and the energy savings could be large. Biotechnology will be a significant factor in improving livestock. Technological progress will improve the competitiveness of American agriculture and will be useful to developing countries.

3.1.1.4 Electricity

Recent developments in ***superconductivity*** have excited interest in new applications. It now appears that practical devices (generators, motors, storage systems, and transmission lines) can be made using materials that exhibit zero electric resistance at easily achieved temperatures. Previously, all known superconductive materials had to be cooled to nearly absolute zero, which is prohibitively expensive for most applications. Many uncertainties have to be resolved before these devices become available; but if the research is successful, the economic payoff in higher efficiency, newly feasible applications, and equipment exports could be substantial.

Virtually every power-consuming process and product can be improved by advances in ***power electronics***, merging power control with microelectronics. Utilities will benefit from the advent of smart power through improvements in the productivity, longevity, and efficiency of power plants and transmission and distribution networks. Greater end-use efficiency and equipment exports could also provide major economic benefits.

3.1.1.5 Advanced conversion to electricity

The production of electricity by steam turbine generators grew steadily more efficient (from 14% in 1925 to 33% in 1960) until 1960. For several reasons, new steam plants today are no more efficient than they were in 1960, and there is little expectation of significant improvement in the near future. Yet electric power generation now consumes a large and growing share of all primary energy, so there is strong incentive for seeking new ways to raise efficiency.

The most promising option for increasing the efficiency of electric power generation is the gas combustion turbine. Both large-size industrial turbines and smaller ***aeroderived gas turbines*** (derived from aircraft jet engines) will have more important roles in power generation. Both types have benefited from military R&D which has resulted in better turbine blade materials and designs, allowing combustion temperatures (and hence efficiencies) to increase. Because of high maintenance and fuel costs and low efficiency, utilities have used industrial

turbines primarily for peaking, but recent advances have improved both reliability and efficiency. In 1960, the largest industrial turbines could produce 25 MW(e) in an open cycle at an efficiency of 25%. Today, they can produce 150 to 200 MW(e) at 35% efficiency; and in combined cycle with steam turbines, the efficiency can increase to 45 to 47% (based on higher heating value of natural gas).

The aeroderived gas turbine is designed to accommodate gas flows that are considerably in excess of their nominal ratings, which facilitates heat recuperation via steam injection. Hot gases leaving the turbine are used to produce high-pressure steam which is injected into the turbine combustion chamber to increase power. This variation is called STIG (steam-injected gas turbine), and a straightforward improvement in STIG is to pass part of the incoming compressed air for combustion through the turbine blades to cool them, thus permitting higher combustion temperatures while heating the combustion air. This intercooled steam-injected gas turbine (ISTIG) will boost efficiency to nearly 50%, and technology transfer from future generations of jet engines should raise efficiency to over 50% [see Williams and Larson (1988)]. Chemical recuperation (using the waste heat to process the fuel into a higher heating value) could raise it even further. These turbines could produce far-reaching changes in the electric utility industry, especially if they can be used with coal (or biomass) gasification employing hot gas cleanup.

Three evolutionary developments have increased the attractiveness of the direct ***Brayton cycle*** power plant using a modular high-temperature gas reactor (MHTGR), the advantages of which are presented under Nuclear Power in this chapter. Recent studies indicate that a Brayton cycle plant that could be built using existing materials and within existing design codes would be cost effective and have an efficiency of 45 to 50%. The three evolutionary developments are the shift in design from the large HTGR to the MHTGR, the development of compact heat exchangers, and the advent of reliable, high-efficiency solid-state power electronics.

A recent development in energy conversion is the ***Kalina cycle***, which is similar to the Rankine cycle on which conventional steam turbines work but could be 10 to 20% more efficient. The Kalina cycle has an upper temperature limit and will probably be used as the bottoming cycle in a combined cycle power plant. Unlike the Rankine cycle, the Kalina cycle varies the composition of water-ammonia mixtures to optimize the thermodynamics within the cycle, whereas the Rankine cycle does not. Other than this one modification, the equipment would be identical to present systems and would require no other changes in technology or materials. Thus, the Kalina cycle could easily be transferred into practice at utility power plants if the economics and operating characteristics are confirmed at the 3-MW experimental plant scheduled to be built in Canoga Park, California, by early 1989. However, the equipment required to operate on the Kalina cycle is complex, which can lead to unexpected cost escalation and operational problems, and the ammonia must be tightly contained to prevent occupational health impacts.

Fuel cells have long been considered a potentially attractive source of electricity because of such advantages as the fact that they are not forced to operate at extremely high temperatures to achieve high efficiency. In fuel cells a reaction occurs between a replenishable supply of fuel and oxygen to produce the electricity, sometimes at over 50% efficiency. However, problems—including high costs and short lifetimes—have been encountered. Improvements are expected in the most commercially developed fuel cell, the phosphoric acid fuel cell (PAFC), but it is unclear if they will be adequate considering the current cost of $2000 to $3000/kW.

The molten carbonate and solid oxide fuel cells (MCFC and SOFC) appear to have potential for overcoming problems of other fuel cells. Both operate at sufficiently high temperatures to make cogeneration feasible, further increasing efficiency. They use methane, which in principle could be produced from coal; but if the methane is not cleaned to almost surgical standards, contamination may reduce the lifetime of the fuel cell. Neither requires the costly materials that must be used in the PAFC, but both entail materials and manufacturing difficulties.

In addition, advanced fuel cells may prove important for powering vehicles because of very low emissions of NO_x and hydrocarbons when using methanol as a fuel. Both monolithic solid oxide fuel cells (operating at high temperatures but with high power density and without a reformer) and proton exchange membrane fuel cells (operating at much lower temperatures but with a reformer to generate hydrogen) are interesting possibilities

Hot gas cleanup would avoid the major energy losses involved in coal or biomass gasification/combined cycles and pressurized fluidized bed combus-

tion; the output gas must be cooled before it can be cleaned sufficiently to be run through a combustion or Brayton turbine without eroding the blades. However, the clean-up equipment itself erodes and fouls quickly with hot particulates, so new materials and designs are required. This technology is likely to be difficult to develop, but significant gains in energy efficiency could result.

3.1.1.6 Storage

Electricity generation as well as some forms of renewable energy can benefit greatly from storage: the former because the units least expensive to operate (usually coal and nuclear baseload plants) cannot be used to meet cyclical demand, and the latter because energy is often not there when it is needed. The widespread adoption of electric vehicles depends on better batteries.

Advanced batteries will have much higher power and energy densities than the existing lead acid technology (which is also improving) and will be more efficient, less costly, and better able to handle deep discharge cycles. Promising examples of advanced batteries include sodium/sulfur, lithium-aluminum/iron-sulfide, sodium/iron-chloride, and aluminum/air. Significant progress has been made with R&D on advanced batteries in recent years, but two major applications are pending. Electric vehicles have so far exhibited inadequate performance and economics, but they could potentially offer major fuel shifting and environmental advantages. Similarly, utilities could use coal- or nuclear-generated electricity stored in batteries during off-peak hours instead of oil- or gas-fired turbines to meet peak loads. Alternatively, high-temperature superconducting coils may ultimately provide electricity storage for load leveling, as already noted. Widespread use of photovoltaics virtually requires advanced batteries of reduced cost. None of these applications is likely to be widespread in the near future, but all have considerable potential.

Thermal storage is aimed primarily at solar technologies (solar thermal electric and passive solar) and industrial energy processes that exhaust heat intermittently and require it at other times. Hot fluids can be stored in a tank, but the cost is high relative to the value of the energy contained. Research is focused on fluids such as molten salts and on chemical process and phase changes that absorb the energy and release it as needed at the required temperatures, ranging from -40 to 1000°C.

3.1.2 Energy Sources

3.1.2.1 Petroleum

Approximately 34% of the total amount of oil in most fields can be recovered by conventional production technology. ***Enhanced oil recovery*** (EOR), a collection of technologies, can increase this yield. Several techniques, including water and steam flooding and CO_2 injection, are already in commercial use. More advanced chemical flooding, miscible flooding, and microbial techniques show considerable promise. The actual increase in oil production that will be realized by flooding techniques is highly uncertain but is predicted to be 3% of the original oil in place (OOIP).

Another promising type of EOR is geologically targeted infill drilling (GTID). After an oil field has been exhausted by conventional production techniques, a substantial amount of mobile oil remains behind in inhomogeneous geological formations. Most of the remaining mobile oil could be recovered by drilling on an ever closer well spacing and by completing wells at ever smaller intervals. However, the random approach would require drilling and completing a large number of wells and would not be economical. Improved ***field characterization techniques*** would permit the cost-effective recovery of more of the unswept mobile oil. GTID might permit the recovery of 8% of the OOIP. Thus, the two forms of EOR (flooding and GTID) might facilitate recovery of 11% of the OOIP and raise the recovery rate from 34 to 45%.

EOR may be one of the most productive R&D investments. Presenting few problems of institutional adaptation, it directly addresses the most valuable form of energy (oil) and is likely to place a cap on oil costs. In addition, for the most part, EOR is environmentally benign since it is applied outside the biosphere. The United States would also benefit from significant exports of materials and services, and the rest of the world would benefit from additional production.

3.1.2.2 Natural gas

In the past, the major restraint on the use of gas has been the concern that reserves were very limited. It now appears that ***unconventional gas*** technology under development may make available large reserves of gas at two to three times present wellhead prices ($1.67/million Btu). The four major

forms of unconventional gas are tight sands, Devonian shales, coal seams, and geopressured brines. Tight sand formations appear to contain about 600 trillion cubic feet (TCF) (current annual U.S. production is about 16 TCF). Recovery of this resource would be expedited by research in characterizing the reservoirs and by gas stimulation through hydraulic facturing. Devonian shales are also a major resource (about 400 TCF). Many wells have been drilled into Devonian shales, but gas recovery is slow and uncertain. Further research is needed on gas flow in the shale and on stimulation techniques. Coal seams are another source of gas (perhaps 400 TCF). Recovery of this resource would not only provide valuable energy but also reduce the danger of coal mine explosions. Advances in drilling, fracturing, and dewatering are required to exploit coal seams that are not close to the surface. The estimated size of the geopressured resource is 270 to 2800 quads of methane and 160 to 1600 quads of heat, but better understanding of well performance over time and reservoir dynamics is needed to evaluate the economic potential.

Improved ***surface exploration techniques*** are likely to help in the search for conventional gas fields that had been missed when the object of most exploration was oil. In addition, smart drills capable of measurements, new bit designs, and new materials for deep drilling can make formerly uneconomic fields (i.e., those with gas below 10,000 ft deep) feasible to develop. Both improved surface exploration techniques and improved drilling could help produce gas at competitive prices.

Increased production of gas, if sustainable for 50 years, would have profound effects on how we view the energy problem. It would help prolong the present energy system, avoiding drastic and expensive changes. If some coal (burned in power plants or converted to synthetic gas or liquids) can be replaced by gas, the rate of production of CO_2 and other pollutants will be reduced. The advanced combustion turbines and fuel cells discussed previously would be even more attractive if gas were a long-term option. Gas can also substitute for oil in case of emergencies or steep oil price rises.

3.1.2.3 Coal

The United States has enough coal to last hundreds of years, even at greatly expanded rates of production. Coal is thus a major factor in both short- and long-term energy projections. However, coal is inconvenient to use and contains contaminants that cause serious pollution unless controlled. Research has focused on ways to burn it more cleanly and economically and on conversions to liquid and gaseous fuels.

Technologies for improved burning of coal include developing ***oil substitutes*** such as coal-water mixtures and micronized coal. Both can be handled as liquids, which are much more convenient than solid fuels, and both may be usable as fuels in appropriately modified oil burners, thus enhancing fuel flexibility. Results to date for coal-water mixtures show promise for reducing handling costs (especially when the coal is supplied by a slurry pipeline) and for control of combustion to reduce NO_x emissions. This technology is on the verge of being commercialized, but problems of keeping the coal suspended and erosion of burners can still be serious. Micronized coal, pulverized to a fine powder, is not as developed as coal-water mixtures, though some units have been marketed. The fine particles make possible the removal of almost all the ash and much of the sulfur, which would greatly reduce emissions. The reliability of the pulverizers must still be demonstrated, as must the long-term compatibility of other equipment with this new form of coal.

Fluidized bed combustion (FBC) units burn coal particles suspended in a stream of air. The coal is mixed with particles of limestone, which captures the sulfur from the coal. There are two types of fluidized bed combustion: atmospheric (AFBC) and pressurized (PFBC). AFBC is a recently commercialized technology, but many refinements are still possible to improve operability. When perfected, AFBC is likely to be the coal-burning technology of choice for many industrial applications (and will probably displace oil used for such purposes) since pollution control is relatively easy. PFBC differs from AFBC in that the combustion chamber is pressurized to several atmospheres, greatly reducing the size of the equipment and permitting factory construction of relatively large units that can be delivered by barge. In addition, operation with a combined cycle for higher efficiency is possible. The hot pressurized combustion gases power a gas turbine, while the turbine exhaust gases generate steam for a steam turbine.

Coal-water mixtures would be very appropriate for feeding a PFBC because moving a solid fuel into a pressurized vessel is difficult; the energy absorbed as the water turns to steam is partially recovered in

the exhaust turbine. However, hot gas cleanup may be required for effective combined cycles to prevent erosion/corrosion of the turbine blades. Other problems to be addressed involve load control and equipment reliability. PFBC pilot plants have been operated successfully, and the concept is promising for the clean, efficient combustion of coal in both industrial and electric utility applications by the end of the century.

Bioprocessing is a relatively recent method for cleaning coal before combustion. Certain pilot plants use microbes to facilitate the removal of pyritic sulfur from coal. The process is predicted to become competitive with traditional cleaning methods. The much more difficult removal of organic sulfur is also possible, but the research is still in an early stage. Through biotechnology, microbes and/or enzymes may be produced to generate liquid or gaseous products from coal, possibly while still in the ground. Advances through biotechnology may be very significant, but research is still preliminary.

If coal is to eventually replace oil and gas on a large scale, it must be converted into more convenient forms for transportation and other uses. In the early part of this century, ***gasification*** of coal was quite common until coal gas was displaced by natural gas. New processes have been developed, but all of them are still considerably more costly than natural gas. Nevertheless, gasification has such great potential that work is continuing, and two applications may permit early deployment: feedstocks for chemical plants and fuels for combined cycle powerplants. In both cases, the gasification process itself must be made more efficient. Research opportunities include an improved system to continuously feed the solid fuel into the gasification chamber, increased flexibility of the gasifier to accept a wide range of coals, and better environmental protection technologies. Improved waste heat recovery could also raise efficiency. Combined cycle applications would benefit from hot gas cleanup to reduce thermal losses.

An alternative approach to gasification involves the use of unmined coal. Combustion is controlled underground to produce gas. The simplicity of the process results in low costs, but many serious environmental questions remain. It is also possible to make high-Btu gas equivalent to natural gas from coal, but the process is uncompetitive at present prices. The economics of high-Btu gas would be improved with the development of catalysts to raise the efficiency of methanation.

The CO_2 emissions from the production (and combustion) of methane from coal are a factor of 2.6 higher than the emissions from the combustion of natural gas because a reaction between coal and water is used to generate the hydrogen required to convert coal to methane. A promising R&D option is to use nuclear power to produce the hydrogen, thereby eliminating the CO_2 emissions from the production of methane from coal.

Pilot plants have demonstrated the feasibility of several technologies for coal ***liquefaction***, but all the technologies tested have proved too expensive to compete with petroleum. However, advanced processes show promise for increasing efficiency and reducing costs. Coal liquefaction will not be competitive soon, but it and biomass (discussed in this chapter) offer the best potential for supplying large amounts of liquid fuels to keep the transportation fleet operating in its present mode if petroleum shortages develop and prices rise considerably. A two-stage, direct liquefaction process is now being tested, and various catalysts could substantially improve the economy of the reactions. Indirect liquefaction (first gasifying the coal, then converting it to liquid) may be even more expensive than the direct process, but it has been used extensively in South Africa and elsewhere. The environmental impacts of indirect liquefaction may be easier to control than impacts for direct liquefaction, especially impacts related to emissions of carcinogenic compounds.

3.1.2.4 Nuclear power

Despite all the problems of the present generation of reactors, nuclear technology offers some major advantages and some impressive successes. The nearly 100-GW(e) capacity that nuclear power contributes to the electric grid supplies nearly 20% of electricity sales and will be essential as reserve margins shrink and alternative fuel prices rise. A major advantage of nuclear power is that it eliminates emissions of CO_2 and the pollutants that cause acid rain and other environmental problems. In addition, there is no inherent reason why future nuclear reactors cannot be economically competitive choices if the public is satisfied that the existing problems of safety, reliability, and costs have been solved. Safely extending the lifetimes of reactors would result in long-term energy benefits.

Public acceptance of nuclear power will be enhanced by ***improving existing light-water reactor***

(LWR) technology. If the average performance of existing power plants can be improved so that load factors are increased from the present value of 60% to about 75% (achieved by several other countries using the same technology), the benefits would be substantial. The increased availability of low-cost, low-impact electricity would improve economics and moderate the need for additional capacity. Furthermore, better operation of existing plants is essential for improved public opinion on nuclear safety.

Specific improvements may include further development of probabilistic risk assessment (PRA) and its application to all operating reactors to identify any weak points and ensure that all reactors meet reasonable standards. The problems that have caused shutdowns, including human factors, can also be analyzed in an effort to improve operations and maintenance. Existing analog control systems are old and unreliable; thus, advanced automated digital control systems offer the potential for both improved reliability and improved human-machine interface.

Although no reactors are expected to be ordered over the next few years, nuclear power may still be a desirable part of the future generating mix. Overcoming the barriers to a nuclear revival is far more likely if reactors significantly better than the existing generation are available. Wider safety and operating margins will be built into the advanced LWR designs, and they should be at least competitive economically with present designs. At this point, it cannot be predicted whether advanced designs will be adequate to provide reassurance that current concerns have been addressed.

U.S. companies, in collaboration with Japanese partners and with joint DOE/EPRI support, are collaborating on an advanced LWR (ALWR) design program focused on two concepts: an evolutionary plant design and a more revolutionary design approach that incorporates new passive safety features. The evolutionary design features improvements such as digital control, improved human-machine interface, and better components.

Several alternative concepts to ALWR are passively safe reactors so forgiving that no operator action and no active safety systems would be required to contain any credible accident without off-site release of radioactive materials or serious damage to the reactor. ORNL researchers believe that the most promising passively safe reactor is the ***modular high-temperature gas reactor*** (MHTGR), though alternative passively safe reactors (the PIUS, or process inherent ultimately safe, LWR of Swedish design and various liquid metal reactor designs) have strong advocates.

The key passive safety features of the MHTGR design are the high-temperature structural integrity of the fuel particles and the thermal properties of the reactor core. The core consists of multilayered ceramic and carbon-coated fuel particles placed in graphite structural blocks. Fission products are retained within the fuel particles which have ceramic coatings that can withstand extremely high temperatures (up to 1800°C) without damage. Temperatures are maintained well below this value by natural convection and conduction to the surrounding earth, even with the failure of pumped active cooling systems.

Because of its modest unit size and passive safety features, the MHTGR is well suited to export markets, especially in developing countries. As mentioned earlier, this concept offers future applications in high-temperature, high-efficiency gas turbine energy conversion systems and high-temperature process heat systems.

If a worldwide commitment is made to major reductions in CO_2 emissions to the atmosphere, the major technological options are improved energy efficiency and nuclear power. If a decision is made to deploy nuclear power on a massive scale (several thousand gigawatts worldwide), R&D will be required in order to demonstrate commercial-scale nuclear fuel recycle and breeder technology or other resource extension approaches such as extracting uranium from seawater, the fusion/fission hybrid, and accelerator breeders. The system of choice is the ***liquid metal fast breeder reactor*** (LMFBR).

Over the past three decades, LMFBR technology has been developed as the result of a major effort in the United States, Western Europe, and Japan. The continuing R&D effort aimed at base technology development will maintain expertise and support advances in the safety and economics of the breeder reactor and fuel recycle technology.

One of the major reasons for the loss of public confidence has been the lack of demonstrated ***radioactive waste management techniques***. R&D is required for dealing with high- and low-level waste and decommissioning nuclear reactors. Waste disposal is fundamental to a revival of the nuclear option. Exhaustive efforts must be made to characterize the site chosen in Nevada for commercial high-level waste disposal and to examine all potential means by which nuclear material could escape.

We do not know the conditions under which further growth of nuclear power will be accepted. Better understanding of such conditions may be essential to avoiding false starts in developing advanced technology. Obviously, such conditions may be a moving target influenced by many factors, but finding ways of measuring such conditions and involving representatives of constituencies with various viewpoints in technical decision making will be very important.

3.1.2.5 Fusion

The technical problems facing the fusion program are formidable. Several more decades of intensive research will be required before it is known whether an economical, operable reactor can be built.* Because fusion is unlikely to make a large energy contribution within the next 50 years, it should possibly not be included with promising energy technology R&D options; however, it is included for two reasons. First, no other technology has as great a potential for producing huge quantities of energy with minimal environmental and social impact. Second, the program is pushing the frontiers of knowledge in several areas, and considerable benefits may derive even if no feasible reactor is developed. For instance, microwave sintering and plasma etching are spinoffs of the fusion program that promise to revolutionize the preparation of certain materials.

The key element in the fusion program is the ***reactor system*** itself. The most promising system now uses magnetic field confinement to contain the reaction. An alternative, using lasers or particle beams to initiate the reaction (inertial confinement), is being pursued largely for military purposes, but it may eventually prove appropriate for power reactors also. Fuel cycle technology of a relatively straightforward nature will also be necessary. The ***fissile fuel breeder*** uses fusion technology to provide fuel to fission systems, and it might become a successful competitor to the LMFBR.

3.1.2.6 Biomass

Fuels derived from plants have the potential to become major components of our energy system. A considerable amount of wood and waste products is already burned directly, but the greatest contribution will depend on biomass culture and conversion to more useful products. We estimate that the United States could produce as much as 14 quads of liquid fuels from biomass (Vol. 2, Sect.2.4). If there is a worldwide effort to reduce CO_2 emissions, biomass could be a major source of liquid fuels for transportation.

The DOE biomass research program is directed at producing alcohol fuels, oil, and gas. In all cases, R&D will focus on three areas: production, collection, and conversion. Advances in all three areas are necessary for biomass to be economically viable, but the greatest potential for cost reduction is in conversion.

Feedstock development encompasses the production of both terrestrial and aquatic crops. Breakthroughs from breeding and genetic engineering are creating the capability of raising the growth rate of woody and herbaceous terrestrial crops by a factor of five or even more. Various algae that are being developed produce hydrogen directly or can be used to produce synthetic oil. Other algae and emergent plants are also promising for biomass, but generally terrestrial biomass will be much more significant than aquatic. Research also focuses on developing plants that are productive over a wide range of environmental conditions and are disease resistant. Progress will depend on advances in physiological research and biotechnology.

Different forms of ***conversion technology*** are required depending on the type of fuel needed. Ethanol is produced by fermentation. Wood and herbaceous products have greater ultimate potential for the production of ethanol than food crops, but the fermentation process is more difficult. The wood or other material must be broken down into sugars that can be fermented. Among various processes under development, the enzymatic process appears to hold the most promise, although it is the least

*At the time this manuscript was completed, the announcements of the discovery of electrolytically driven cold fusion were being made. Obviously, if the claims are substantiated, the implications could be revolutionary.

developed. Acid hydrolysis is also promising. Many different yeasts, as well as bacteria and other fungi, are being investigated because the various sugars that are produced during fermentation cannot all be digested by any one yeast. Some of the separation technologies discussed in this chapter may improve the prospects for economic fermentation processes.

Wood and other biomass can be liquefied or gasified by methods similar to those that are applicable to coal. Direct liquefaction results in oils or tar that can be upgraded to gasoline or other liquid fuels. Thermochemical pilot plants have been operated, including one with a catalytic, low-temperature, high-pressure reactor. This process is potentially a high-payoff area of research, but many problems have to be solved. An alternative approach is to grow plants that produce natural oils—for example, several plants and microalgae produce hydrocarbons with 16 to 20 carbon atoms. About 0.7 quad of soybean oil is already processed, and this amount might be doubled if improved plants are developed. These natural oils resemble diesel fuel, but upgrading is necessary before they are usable.

Gasification can be accomplished either with anaerobic digestion to produce methane or partial oxidation to produce carbon monoxide and hydrogen. Anaerobic digestion of sewage sludge and some other wastes is already done commercially. Further developments may allow the processing of energy crops at costs that are nearly competitive.

A final area that deserves mention is ***municipal solid waste processing***. Solid waste is turning into a major problem for many communities as landfill sites become harder to find and air pollution restrictions limit incineration. This waste contains paper, food products, and other biomass with a significant energy content. Some efforts to recover the energy via incineration with heat exchangers and steam turbines (and environmental controls) have been successful, but a great many problems have also been experienced. If sorting techniques for recovering metals and other recyclable noncombustibles were perfected (and the incinerator and pollution control equipment improved), a modest but economically attractive energy contribution could be gained in the process of solving the disposal problem. The gain includes that which is realized because recycling of materials is generally less energy intensive than producing them from virgin resources.

3.1.2.7 Solar electric

Sunlight can be converted directly into usable energy in a variety of ways. ***Photovoltaic energy conversion***, which directly converts sunlight to electricity, has experienced a steep drop in price and a major increase in efficiency over the past 15 years (Fig. 2.16). Although still expensive, photovoltaics is the technology of choice in applications such as those in remote sites and for batteryless calculators. Further advances in crystalline silicon, amophorous silicon, and other thin films promise to increase efficiency and reduce costs significantly within a few years. Multijunction concentrator cells could eventually raise efficiency to about 40%. Improved manufacturing techniques as well as increased manufacturing scale will cut costs even more. Utility companies whose loads peak in the summer may find photovoltaics competitive, as output of photovoltaic cells closely tracks air conditioning loads. Photovoltaics probably holds more promise than any other technology for untended, independent applications such as in residences.

The technology of ***solar thermal*** energy is quite different from photovoltaics, although the applications can be similar. Sunlight is focused by mirrors or lenses onto a receiver that contains water or another fluid to conduct the heat to an engine that generates electricity. A distributed receiver is an independent unit consisting of mirrors (or lenses) and a receiver/engine of perhaps several tens of kilowatts. Alternatively, a larger engine might share the output of several receivers. Another concept involves a stationary central receiver that collects the energy from many mirrors, each of which separately tracks the sun. The largest central receiver currently in operation has a capacity of 10 MW(e). Advances such as lightweight mirrors have sharply reduced the cost of solar thermal electricity, and further improvements are expected. Molten salt as a heat-transfer medium is testing well. Stirling engines would be particularly appropriate for solar thermal energy conversion, especially for distributed receivers, and recent developments suggest that they may finally be nearing readiness for commercialization. Solar thermal lacks the market niches of photovoltaics and will probably never be able to run untended, but it is more efficient (over 30% conversion of sunlight to electricity has been demonstrated) and may prove less expensive. Storage capability can be incorporated easily, which improves desirability for utility applications.

Both photovoltaic and solar thermal technologies could be expanded rapidly if their economics prove competitive, but that is unlikely at present fuel prices. Thus, their energy contribution is uncertain, though it could be large. Both offer major environmental advantages. Along with biomass and nuclear energy, they are the supply technologies that would be relied upon if CO_2 accumulation becomes a major problem within the next several decades. Both technologies may also become significant exports, particularly beneficial for less developed countries where remote applications are common. Photovoltaics and solar thermal technologies are popular with the public and could be incorporated in the existing electric system with no great problem. However, neither can power a stand-alone electric system without storage, and reliable storage for extended periods of cloudy weather, especially in winter, is very expensive.

Although ***hydroelectric*** power is a mature technology, a small investment in R&D could produce great benefits, significantly increasing the hydro generating capacity for the United States. The installed capacity of 90 GW produces about 300 billion kWh/year. Most people regard the period from 1930 to 1940 as the golden age of hydro (the Tennessee Valley Authority, Hoover Dam, and Grand Coulee Dam were built during the period); however, hydro capacity has more than doubled since 1960.

In our review of hydro resources, we have learned there are 1948 sites that have a potential combined capacity of 46 GW (Vol. 2, Sect. 2.4). These sites include 1407 existing dams, and new dams would be required at the remaining 541 sites. R&D focusing on the analysis and minimization of the environmental effects of hydro is required to overcome the legal and institutional barriers to the development of these hydro resources. For example, research is needed to develop and validate methods for the specification of in-stream flow requirements for fish and other aquatic life. Also, the technology for allowing fish to bypass dams as they migrate downstream should be improved.

An immature but promising technology is the generation of electricity using ***wind turbines***. As a result of federal and state tax incentives, the installed capacity of wind turbines increased rapidly from 0.3 GW in 1983 to 1.5 GW in 1988, when the tax incentives expired. R&D is required to develop a power electronics package for a wind turbine system. Early wind turbines operated at a constant rotor speed to comply with the constant frequency required by the electrical utility. Through the use of suitable power electronics, an advanced wind turbine can operate at variable rotor speeds and provide constant frequency power to the utility. A variable-speed wind turbine would provide more energy and have smaller structural loads, reduced weight, and a longer life.

Like the sun, wind is intermittent and varies significantly from one region to another. Photovoltaics, solar thermal, and wind turbines will probably be used initially in a fuel-saving mode.

3.2 CROSSCUTTING TECHNOLOGIES AND AREAS OF SCIENCE

In the R&D process, new technologies are built on the foundation created by basic science research. The crosscutting technologies are intermediate between basic and applied research. The new technologies created by crosscutting R&D may find applications in many different energy technologies. This section reviews some of the most promising opportunities for R&D among the crosscutting technologies.

Microelectronics and sensors have been mentioned several times in this report. "Smart systems" will play a significant role in improving efficiency in industrial processes, buildings, and transportation. They will also be important in improving the efficiency, economics, safety, and environmental protection performance of the energy supply system—from finding and producing fuels to the conversion to more useful energy forms and to the transmission and distribution of electricity, natural gas, and other carriers.

Significant developments will come in cheaper, more sensitive, and miniaturized sensors which can be integrated with microelectronics for customized smart control and diagnostics. The range and type of parameters which can be measured will be extended, and sensors which can withstand harsher environments will be invented. The better integration of smart sensors for system control, optimization, and failure identification and diagnosis represents an area of opportunity, the full implications of which are only beginning to be appreciated.

Advanced materials may affect virtually every aspect of energy supply and use. Superconductors are the most dramatic new development, but applications depend on new materials with properties

such as ductility and machinability. The lack of appropriate high-temperature materials has always been the limiting factor on the efficiency of automobile engines and electric generating equipment. Materials with improved resistance to corrosion and erosion, especially at high temperatures, are essential for gas turbines fired by fuels with particulate matter or for hot gas cleanup in coal gasification. High-strength, lightweight materials would be particularly useful in transportation and probably in other applications as well. Problems in energy storage relate to materials, especially for advanced batteries, thermal storage, and metal hydrides, as well as superconducting coils. Disposal of nuclear and other toxic wastes also depends largely on materials for containment. Better fundamental understanding of coupled materials will lead to materials by design (i.e., the knowledge to fabricate materials—composites, alloys, plastics, and ceramics—which exhibit the properties needed for specific applications).

Biotechnology is very important for the production of energy crops, but it also holds promise for improved paper and pulp manufacture, the direct production of hydrogen, chemical feedstocks, coal cleaning, and enhanced oil recovery. Several enzymes and bioprocessing techniques are also promising. One potentially important development might be enhanced biofixation of CO_2 using a more efficient form of the enzyme Rubisco, which is essential to plant photosynthesis. In addition to product development projects, biotechnology R&D must include a substantial basic research component, especially on understanding the risks of genetic engineering.

Separations have been mentioned in connection with the industrial sector. A range of potential applications exists for improved membranes, including use in gaseous separations and the separation of alcohols from biomass fermentation using less energy than distillation, and basic research may open other avenues. Membranes and supercritical fluid extraction might eventually lead to a viable CO_2 scrubbing process. Ultrapurification techniques could be useful for chemical production and waste treatment. Seawater can be a source of vast quantities of minerals, including uranium and deuterium, as well as potable water in arid regions, with the proper separations that are economical.

Combustion science fills some surprising gaps in the knowledge of what actually takes place during combustion. Advances could lead to optimization of both efficiency and environmental emissions for fossil fuels and biomass. All sectors using combustion—transportation, the electric generation industry, and buildings—could benefit. Specific developments might include combustion enhancement techniques, fuel switching capabilities, improved use of sorbents to remove SO_x and NO_x, knock control in automobile engines, and combustion control of municipal incineration.

Advances in *electrochemical processes*,* including photoelectrochemical processes, may be the keys to advanced batteries, fuel cells, artificial fixation of CO_2, and production of hydrogen. Better electrochemical technology may lead to more efficient and economical approaches to producing aluminum, magnesium, chlorine, and other materials.

Geosciences can contribute to enhanced oil recovery and unconventional gas production techniques as well as exploration. Understanding of geosciences is also vital in nuclear waste disposal and oil storage in the strategic petroleum reserve. Developments in geothermal energy are likely to depend on better understanding of processes within the earth. Progress is dependent on developing better subsurface sensing and imaging techniques, on improved theories of structure, chemistry, and mechanics, and on improved models of multiphase flow.

Effluent management can help make opportunities out of problems by recovering useful products from waste streams or at least reducing the problems by removing pollutants. Energy production results in many such waste streams, especially from combustion and conversion processes. Flue gas scrubbing for SO_x, NO_x and CO_2 is an area ripe for further development. Long-term durability of solid waste forms is a vital R&D objective for radioactive/hazardous materials.

Many of the questions likely to prove critical in planning the future of the energy system involve not hardware or technique development but rather ways to get the right information into the right places so that appropriate decisions can be made.

*In the course of the final review of this document, John Whetten of Los Alamos National Laboratory pointed out that we had missed electrochemical processes as an important crosscutting area. He is right, although we did recognize the importance of the applications of electrochemical proceses in batteries and fuel cells.

Decision making and management research is particularly important for questions involving social risk. An understanding of the way that people come to different perceptions can help in program development and conflict resolution. Another key area may involve the response if CO_2 is confirmed as a major problem. An unprecedented level of worldwide cooperation would be required. A better understanding of international decision-making processes which may be invoked to resolve global environmental issues could be particularly useful in focusing R&D on conflict and policy relevant aspects of these issues.

As has been explained, an effective strategy for moderating the rate of greenhouse change as well as relieving the stress on oil and gas markets is the adoption of more energy-efficient technologies. Encouraging billions of people to adopt energy-efficient technologies will require considerable research into how people decide on investments in energy savings. Too little is known about the barriers to more complete and rapid market penetration of such technologies. Not only are market barriers and failures not well understood, but the effectiveness of various policies which might improve adoption is only beginning to be measured. Decision making in organizations, such as for utility least cost-planning, is a related subject of high priority.

3.3 COMPARISON WITH UNITED KINGDOM STUDY

The Department of Energy of the United Kingdom recently published an analysis of energy technology R&D (U.K. DOE 1987). The study was both an assessment of technology and an appraisal of R&D. The assessment was an evaluation of the future role of technology, while the appraisal required an estimate of the needed R&D and its cost effectiveness.

Table 3.5 compares promising R&D options identified in this study with the attractive options identified in the U.K. report. Our objective is to determine the amount of overlap between the two studies and to identify promising technologies that we might have overlooked. To be included in Table 3.5, an option from the U.K. report must have a rating of EA (economically attractive) or P (promising) in the assessment of technology and an R&D returns-to-cost ratio that is greater than unity for all the scenarios considered in the U.K. study.

The U.K. study defines an essential technology as a component of an energy supply system. Examples of essential technologies are nuclear fuel cycle technologies and technologies for transmitting and distributing gas and electricity. Although there are cost-effective R&D opportunities to improve the essential technologies, we have not included the essential technologies in Table 3.5.

R&D options for Transportation are listed in the first part of Table 3.5. For the energy utilization technologies, the U.K. study analyzed specific R&D projects rather than an aggregation of many projects. For the vehicle and engine design category, they analyzed an advanced diesel engine. However, both ORNL options, "Advanced engine technologies" and "Continuously variable transmission," are compatible with the U.K. "Vehicle and engine design" category.

The U.K. study performed a technological assessment of aircraft design and aero engines and found that the category was economically attractive (EA). Because R&D on aircraft engines is done by a private company (Rolls Royce), it was impossible to obtain enough information to perform an appraisal of aircraft R&D. The U.K. study did not consider automated dynamic traffic control.

The lists of R&D options for the Buildings sector are similar.

For the Industrial sector, the two lists have significant differences. The U.K. study did not consider process changes that could increase energy efficiency; thus, it does not mention catalysts, separations, pulp and paper processes, steel processes, or agricultural techniques. "Cogeneration" is the same as "Combined heat and power." The U.K. study mentions R&D on sensors and controls in several sections of the detailed evaluations.

"Motive power" in the Industrial sector includes R&D on electric motors and overlaps with our category "Power electronics" in the Electricity sector. The U.K. study was completed before the recent advances in superconductors.

In the Advanced Conversion area, the U.K. study did not consider aeroderived gas turbines, the Brayton cycle, the Kalina cycle, or hot gas cleanup. The U.K. study did consider fuel cells, but it was concluded that too little R&D was being conducted in the U.K. to appraise the cost effectiveness of the R&D. The assessment of the fuel cell technology indicated that it was on the borderline between promising and unpromising.

In the Storage area, the U.K. study did not evaluate advanced batteries and thermal storage.

Table 3.5. Promising R&D options identified by Oak Ridge National Laboratory and the Department of Energy, The United Kingdom

Oak Ridge National Laboratory	Department of Energy, The United Kingdom
Transportation	
Advanced engine technologies	Vehicle and engine design
Continuously variable transmission	
Improved aircraft efficiency	
Automated dynamic traffic control	
Buildings	
Heat pumps	Design
Lighting	Management
Smart control systems	Fabric and ventilation
Envelopes	Heating and cooling
Manufactured buildings and components	Lighting and appliances
Computer-assisted design	Passive solar design
Existing building retrofits	
Industrial	
Catalysts	High-temperature process heat
Sensors and controls	Combined heat and power
Separations	Motive power
Advanced heat management	Energy management
Cogeneration	
Pulp and paper processes	
Steel processes	
Agricultural techniques	
Electricity	
Superconductivity applications	Load management
Power electronics	
Advanced conversion to electricity	
Aeroderived gas turbines	
Brayton cycle	
Kalina cycle	
Fuel cells	
Hot gas cleanup	
Combined heat and power	

Table 3.5. (*continued*)

Oak Ridge National Laboratory	Department of Energy, The United Kingdom
	Storage
Advanced batteries Thermal storage	
	Petroleum and natural gas
Enhanced oil recovery Field characterization techniques Exploration and drilling techniques Unconventional gas techniques	Exploration techniques Drilling technology Reservoir engineering Production engineering Offshore technology
	Coal
Oil substitutes Fluidized bed combustion Bioprocessing Gasification Liquefaction	Conventional extraction Large-scale coal combustion
	Nuclear power
Improving existing LWR technology Modular high-temperature gas reactor Liquid metal fast breeder reactor Waste management techniques	Advanced gas-cooled reactor Pressurized water reactor Fast reactor and fuel cycle
	Fusion
Reactor systems Fissile fuel breeder	
	Biomass
Feedstock development Conversion technology Municipal solid waste processing	Combustion of organic wastes Digestion of organic wastes Energy crops
	Solar electric
Photovoltaic energy conversion Solar thermal Hydroelectric Wind turbines	Hydropower

In the Petroleum and Natural Gas area, the two lists overlap substantially. Because U.K. oil is offshore, the study concluded that R&D on enhanced oil recovery would not be cost effective if oil prices are low.

In the Coal area, fluidized bed combustion is included in the category "Large-scale coal combustion." We did not identify any promising R&D options in the mining of coal. The U.K. study considered oil substitutes, gasification, and liquefaction and concluded that the R&D might not be cost effective if the oil and gas prices were low.

In the Nuclear Power area, there is substantial overlap between the two lists. Waste management is included in the U.K. study as an essential technology. The advanced gas-cooled reactor is substantially different from the MHTGR.

In the Fusion area, the U.K. study concluded that fusion was unpromising.

In the Biomass area, there is substantial overlap between the two lists.

In the Solar Electric area, the only technology on both lists is hydropower.

The U.K. study concluded that Photovoltaics were unpromising and the R&D was never cost effective; it further concluded that wind power was promising but the R&D was not always cost effective. The U.K. study did not consider solar thermal electricity. Of course, the U.K. does not have as much solar potential as does the southwestern United States, for example.

To summarize, our comparison of the two lists reveals many areas of agreement and does not identify any promising technologies we neglected.

3.4 ENERGY TECHNOLOGY R&D THAT CAN MAKE A DIFFERENCE

The objective of the work described in this chapter has been to identify energy technology R&D options that can make a difference. A large team was organized, a comprehensive list of R&D opportunities was reviewed, and 50 promising R&D options were identified. In a concluding look at the 50 options in Table 3.2, we will ask the questions, What is unexpected? What is most important? What will make a difference?

In the last 15 years, efficiency has made a great difference. However, improved efficiency is the result of many small changes by millions of people. As we look at the list of R&D options for the end-use sectors, it appears that none of them could make a significant difference by itself; however, the sum total of all of the end-use options could make a large difference.

An R&D supply option that surprised us is the aeroderived gas turbine. Since 1960, the average efficiency of electricity generation in the United States has remained at 33%. The ISTIG, an aeroderived gas turbine, could have an efficiency of 47% or more. A recent paper (Williams and Larson 1988) estimates that ISTIG could be developed and demonstrated in 4 to 5 years at a cost of $100 million (including $40 million for the first unit). It requires essentially no additional R&D, only demonstration.

If CO_2 emissions are to be significantly reduced, two important options are biomass and the MHTGR (or other passively safe reactor). Most advanced technologies produce electricity. However, liquid fuels are an essential input to the transportation sector. Biomass can be used to produce liquid fuels without any net CO_2 emissions. We estimate that biomass in the United States could provide 5 to 15 quads of liquid fuels at costs less than $10/million Btu.

The MHTGR has three attractive features. It is a passively safe nuclear reactor. Using the Brayton cycle, the MHTGR can produce electricity with an efficiency of 45 to 50%. Process heat from the MHTGR can be used to produce liquid and gaseous fuels from coal without any CO_2 emissions in the production process.

Chapter 4
A Balanced Energy Technology R&D Strategy

In Chap. 3, we identified some 50 promising R&D options. These were obtained by reviewing the state of R&D progress in the various energy source and end-use areas. This was the technology-push or bottom-up approach described in Chap. 1. Opportunities are pursued because they are there and, with success, the products should respond to perceived societal needs.

However, approaching the matter by starting with the needs themselves can determine whether the list presented in Table 3.2 is sufficient. Further, because all the R&D options identified in Table 3.2 are being pursued at various levels of intensity, we should inquire whether that intensity of effort is also sufficient.

This chapter defines a balanced energy technology R&D strategy for the country by taking the top-down or societal-pull point of view, in contrast to the bottom-up emphasis of Chap. 3. These are two different ways of getting answers to the question "What might make a difference?" A central purpose is to assess how well the package of promising options of Chap. 3 fits R&D needs over the next 50 years. We should expect a priori a reasonable fit since the criteria used to evaluate the promising R&D options were chosen to represent energy system problems or desirable characteristics. The bottom-up approach of Chap. 3 identifies promising R&D options; the top-down look in this chapter defines societal needs, and the matching of the options with the needs establishes whether the options are sufficient in aggregate to meet the needs. If so, the R&D strategy is balanced.

The goal of R&D is to provide new and improved technologies which yield economically competitive and socially acceptable energy services. In other words, the goal of R&D is to develop technologies which will sell in the market place. Improved technologies which sell are also likely to improve the energy system by enhancing desirable characteristics (as discussed in Sect. 2.6): that is, by reducing costs; reducing negative environmental, health, and safety impacts; improving mobility, availability, reliability, and security; or by increasing long-term economic resources. The technology frontiers for providing services will change over time as the energy system changes, as new technologies penetrate, and as requirements for social acceptability change. Thus, the substantive character of attractive technologies will be in continuous flux.

The goal of a balanced energy technology R&D strategy for the country must be more, however. Not only must the technologies developed sell, but collectively they must also satisfy three basic energy system needs as well:

1. The strategy should help solve existing or imminent energy system problems.
2. It should provide a robust set of options for coping with, taking advantage of, or encouraging future circumstances. That is, it should help move the system in desirable directions, and it should provide insurance against adverse circumstances. In other words, the R&D should provide technological resiliency for an uncertain future.
3. R&D can create unexpected opportunities (e.g., the possibility of room-temperature superconductors). Part of any balanced energy technology R&D strategy should be basic, generic, and

crosscutting research, such as that discussed in Chap. 3, which has a chance to produce breakthroughs that can revolutionize energy technology.

These three needs or objectives of a balanced R&D strategy tend to have different expected time frames. The first is concerned with immediate or imminent societal problems and goals and, thus, may have a relatively short time horizon. The second, concerned with possible future circumstances, is aimed at providing insurance or investment and has a longer-term horizon. The third, new opportunities, has generally the longest but inherently an unpredictable time horizon.

Do our promising options constitute a balanced R&D strategy? To examine that, we need to test the slate for value against energy system problems (as discussed in Sect. 2.5) and for coping with adverse future circumstances or achieving desirable ones.

4.1 THREE FUTURE CIRCUMSTANCES

One of our three basic needs for appropriate R&D strategy is that it provides a robust set of options to ensure adequate energy services under any future circumstances. Of course, the strategy will be reviewed more or less continuously and modified from time to time as circumstances become more clear, but for what circumstances should we prepare?

Initially, we considered a number of scenarios for the future (i.e., high oil prices, low oil prices, extensive new resource discoveries, limited new discoveries, more or less severe environmental restrictions of various sorts, various geopolitical developments and so forth). But there appeared to be two major uncertainties that most strongly influenced our view of R&D requirements to prepare for the future:

1. What will be the future demand for primary energy sources, particularly for oil and gas, by the United States and the rest of the world? How fast will it grow, and what will be the consequential prices and resource base changes?
2. Will the use of fossil fuels over the next 50 years be curtailed because of concern about the greenhouse effect?

We therefore condensed a number of scenarios into three future circumstances that provide a framework for identifying R&D needs. Briefly, these are (1) energy demand grows only slightly; (2) energy demand increases substantially; and (3) the greenhouse effect becomes a controlling factor in energy supply.

4.1.1 Circumstance 1

The United States and many other nations continue to improve the efficiency of energy use in general and oil use in particular to such an extent that demand for primary energy worldwide grows slowly and is closer to the estimates of Williams (1987) for the United States and of Goldemberg et al. (1988) for the world as a whole than to those of IIASA (1981) or WEC (1983), as discussed in Chap. 2, Sect. 2.4. That is, more efficient, economically competitive end-use and conversion technologies (i.e., improved technologies, whether existing or developed in the future) penetrate the market sufficiently to provide for growth in energy services with little or no growth in primary energy use and particularly in oil use.

There are significant forces still operating in the United States which may be sufficient to cause the efficiency of the energy system to continue to improve. Even at current low prices, much of the capital stock is not optimum with respect to energy use, and more efficient technology commonly is still a good buy. Also, efficiency standards provide added incentives to adopt these technologies as capital turnover or expansion occurs. Also, the clean coal initiative may accelerate the repowering of industrial and utility facilities with advanced processes which emit less NO_x and SO_2 and are more efficient than the ones they replace. Such a high-efficiency, low-oil-use circumstance is attractive for several reasons:

1. It may be the least-cost approach to providing energy services for economic growth.
2. To the extent that economically competitive, energy-efficient technologies are used by a country, its international competitiveness would be enhanced.
3. The stress on oil and gas markets would be lessened, leading to improved energy security and an easier situation for developing nations.

4. Adverse impacts of the energy system on the environment and on human health and safety would be reduced, including reduced CO_2 emissions.
5. More time would be available to develop technologies to substitute for oil and gas or to move away from fossil fuels altogether, if necessary because of the greenhouse effect.

Hence, this high-efficiency circumstance provides some important nonmarket benefits—namely, environmental protection and energy security. Improving efficiency economically should be attractive for any nation to pursue and to the extent that it is pursued, it will reduce CO_2 emissions worldwide. It may be, in fact, the best interim strategy for managing the greenhouse effect.

For many reasons, however, Circumstance 1 may not happen. More energy efficient technologies may not have sufficient cost advantages to penetrate the market rapidly. Generally, more efficient technologies have higher capital costs. Investment decisions may be made on the basis of least first cost rather than least life cycle cost, particularly because future prices are uncertain and may fluctuate. Also, more efficient capital stocks may not be introduced rapidly enough to fully offset the increasing demand for energy services. Various market barriers and imperfections exist, including the lack of readily available credible information and know-how.

Further, the more successfully efficiency is practiced, the lower oil and other fuel prices will tend to be, thereby reducing the economic incentives for further improvements. Finally, improved technologies may not come to the market quickly enough, or they may not be attractive enough to cause widespread adoption. Although in Chap. 3 promising R&D options for efficiency improvement were identified in all end-use sectors of the economy and in electricity production as well, we do not know how rapidly the R&D process will deliver successful technologies.

Because Circumstance 1 is so desirable with regard to nonmarket societal benefits, it is assumed that government policies are evoked to encourage (but not coerce) use of high-efficiency technologies which are also economic. These policies are designed to remove barriers and market imperfections.

4.1.2 Circumstance 2

Circumstance 2 results from Circumstance 1 not happening, and demand for primary energy, including oil, rises much more rapidly. In fact, U.S. primary energy demand has rebounded over the last year and a half (of low oil prices), and the rate of reduction of E/GNP has slowed dramatically from the trend of the previous 12 years. Furthermore, the primary energy and oil demand of the developing nations and the centrally planned economies has been growing much more rapidly since 1973 than that of OECD countries, as illustrated by Figs. 4.1 and 4.2. Remarkably, the pre-1973 rate of growth in primary energy demand by the rest of the world (ROW), which includes many of the developing nations, did not slow appreciably in the face of the oil price shocks of the 1970s (Fig. 4.1). Oil demand did slow somewhat but by no means as much as it did for OECD countries (Fig. 4.2).

In this circumstance, the increasing demand doubtless will be met primarily by increased use of fossil fuels and increasingly with coal as oil and gas prices rise. Worldwide, it may be met in part by a continuing growth in the use of nuclear power and other nonfossil sources, particularly hydropower and biomass, but the demand for fossil fuels will also grow. Circumstances 1 and 2 differ quantitatively but not qualitatively with respect to sources; they are both dominated by fossil fuels.

4.1.3 Circumstance 3

In Circumstance 3, the growing concern about the greenhouse effect causes many nations of the world to move away from fossil fuels and to actively promote increased efficiency of energy use and conversion. During the course of this study, we may have witnessed the beginning of a state of affairs which may lead to Circumstance 3. Public awareness of the greenhouse effect has grown much more rapidly than we would have expected. It is manifested by worldwide press coverage of unprecedented proportions and by multiple bills introduced in Congress (U.S. Congress 1988c).

In Sect. 2.5.1.1, we discussed the necessity for adapting to some climate change while preventing excessive changes from occurring. Although research

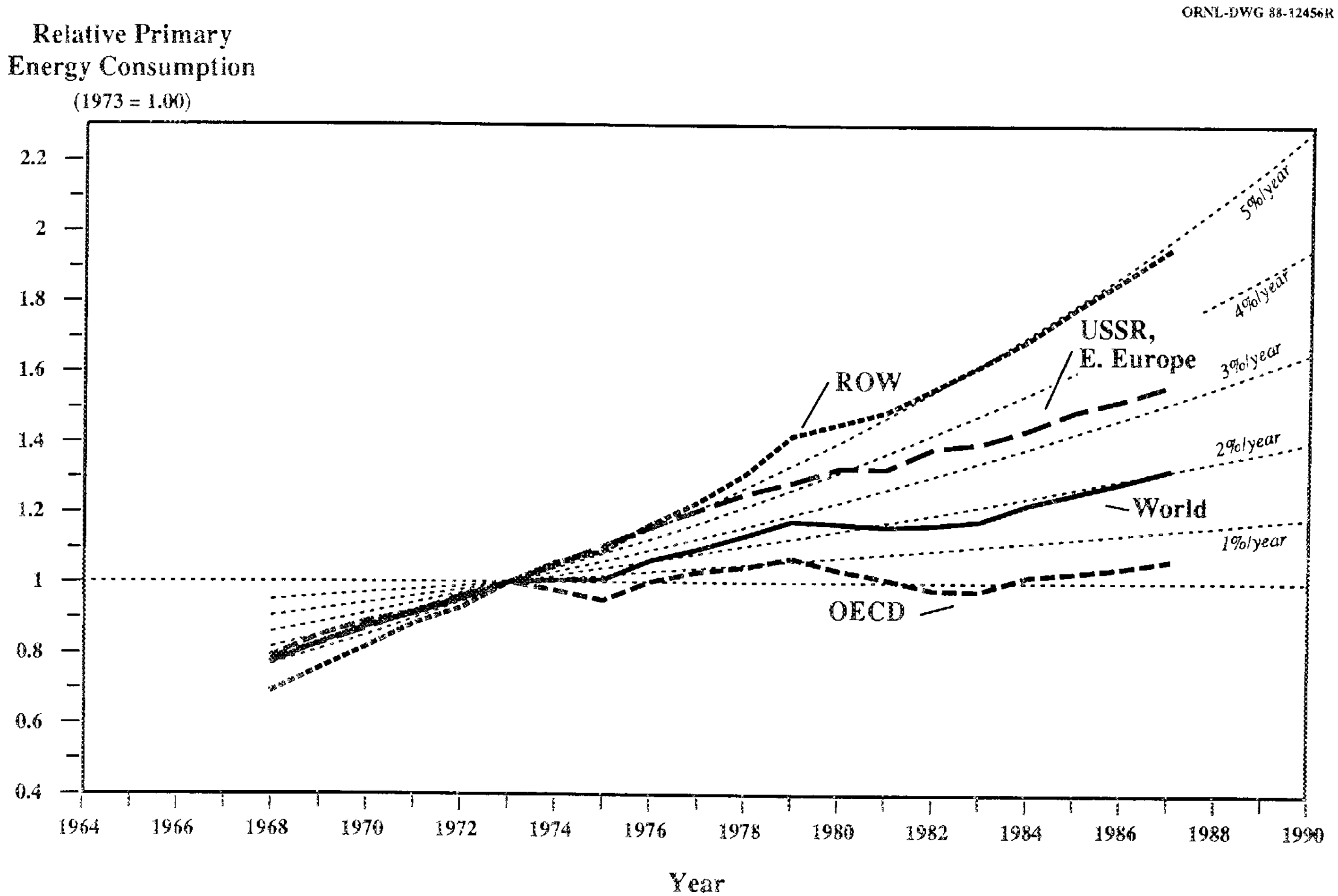

Fig. 4.1. Primary energy use by various nation groups: Organization for Economic Cooperation and Development (OECD) nations; U.S.S.R. and East Europe; and the rest of the world (ROW). All values are indexed to unity for 1973. *Source:* adapted from *BP Statistical Review of World Energy*, British Petroleum Company, June 1988.

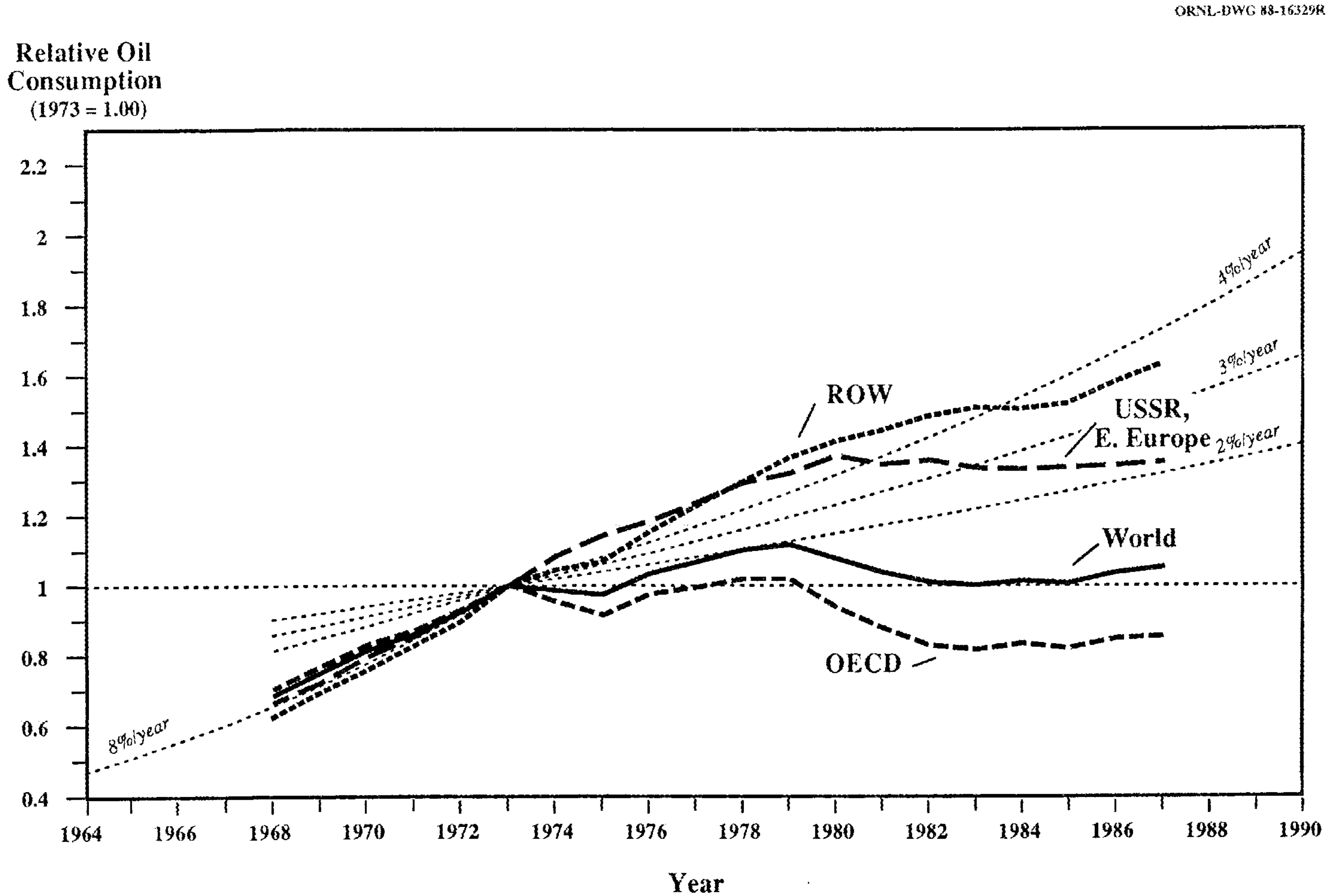

Fig. 4.2. **Oil use by various nation groups and the world.** All values are indexed to unity for 1973. *Source:* adapted from *BP Statistical Review of World Energy*, June 1988.

on adaptation to climate change and its various consequences is essential, we focus here on the role of improved energy technologies in reducing emissions of CO_2 and other greenhouse gases.

At least initially, action does not need to be coordinated among nations to be useful. Action could begin unilaterally here and there.* Some of the proposed legislation, if enacted, would mean unilateral action by the United States. We may be observing a most profound social movement; by comparison, the oil shocks of the past 15 years are trivial. On the other hand, without more tangible evidence that greenhouse effects are occurring, the clamor may die down, and no action may occur for some time.

In Circumstance 3, a number of significant changes must occur around the world, and they may take decades to accomplish. First, there would be an intense emphasis on efficiency improvement, but unlike Circumstance 1, all sorts of policies would be adopted to encourage or force the use of more efficient technologies. Increasing efficiency would likely be the least costly, most effective, and quickest strategy for reducing CO_2 emissions initially. Similarly, in the short run, switching among fossil fuels could have some impact on emissions, depending on the availability of natural gas at the time. Substituting of natural gas for coal would reduce CO_2 emissions by about 40% per Btu substituted, more if the natural gas can be used in the same applications more efficiently than coal.**

At the same time, the substitution of nonfossil energy sources would be encouraged or mandated. At least in the short term, only nuclear power, hydropower, and biomass can substitute for fossil fuels competitively or nearly competitively. Hydropower and biomass are limited resources. In the United States, the estimated expansion potential of hydropower is about 50 GW(e) or about two-thirds of the present capacity but perhaps only 40 to 50% of present energy generation from hydro (see Vol. 2, Sect. 2.4). Similarly, biomass resources are limited, but they can be a significant source of liquids for transportation fuels and of feedstocks for chemicals. Ranney et al. (Vol. 2, Sect. 2.4) estimate a future "optimistic" potential of about 14 quads/year of liquids (net) for the United States. Used with very efficient vehicles, this quantity of liquid fuels could satisfy a major part of U.S. requirements for transportation fuels.

Nuclear power is the only nonfossil source which currently has the potential for large-scale expansion at costs roughly competitive with coal-derived electricity. As we have noted, however, nuclear cannot be expanded much until a number of public and utility concerns are resolved. These include waste management, safety, proliferation, and cost. The latter is likely not to be a major concern in Circumstance 3, but proliferation may be a much more important concern with massive deployment of nuclear power on a worldwide scale as might occur in this circumstance.

Other nonfossil sources are not yet ready to contribute much. Photovoltaics or direct conversion of solar heat to electricity are too expensive even as fuel savers during peak demand periods, and stand-alone systems will require much cheaper storage. Wind power suffers from the same problems. Geothermal sources are generally limited by cost and geography. Other sources, such as wave, tidal, and ocean thermal energy, could have only a limited value in the United States, although there may be useful application potentials worldwide.

If fusion proves technically and economically feasible, it could be the ultimate source in the long term. It is virtually inexhaustible, with substantially

*Although Circumstance 3 may begin with unilateral action, curtailment of CO_2 emissions cannot be fully effective without a coordinated effort involving many nations. If reductions are made by only a few, fossil fuel prices will decline and nonparticipants will be encouraged to increase their use of fossil fuels, offsetting the impact of those nations that reduce their emissions. Of course, efficiency improvement can be pursued aggressively and advantageously by any country regardless of what others are doing. Enough such unilateral actions may or may not add up to effective aggregate behavior.

**An interesting point is that natural gas substituted for coal in electric generation, for example, reduces CO_2 emissions by roughly a factor of two per unit of energy substituted, but the substitution of compressed natural gas (CNG) or of methanol derived from natural gas for gasoline in vehicles would reduce emissions by only 25% in the case of CNG and would actually increase emissions about 10% for methanol because of the losses associated with manufacturing methanol from natural gas. Thus, there can be a conflict between using natural gas to reduce smog and using it to reduce CO_2 emissions.

smaller environmental or safety problems than nuclear fission and, like nuclear fission, it could be deployed massively, independent of geography. It could also be used to breed fuel for fission reactors. However, it is unlikely to be ready for deployment in the next 30 to 50 years.

Hence, nonfossil sources, with the possible exception of nuclear, are not able to compete with fossil sources on the required scale to significantly reduce CO_2 emissions. If nuclear power is unacceptable, the next best source is not very good. That next best is probably biomass, despite its limits. It should be noted, however, that solar-electric, wind, and geothermal power work in a technical sense and can be deployed, albeit at a high cost.

Table 4.1 provides a range of estimates of CO_2 emissions for the United States for the years 2020 and 2040, compared with 1987 levels. The estimates are also shown in Fig. 4.3. Assuming that R&D is successful, the potential contributions of efficiency improvements and the substitution of nonfossil for fossil energy sources are suggested. We have assumed that the estimates of Williams (1987) provide a reasonable indication of the best that can be accomplished through efficiency improvement by 2020, and for comparison we used the base case forecast of the Edmonds-Reilly (ER) model (Edmonds and Reilly 1986), which contains smaller but nonetheless significant gains in energy efficiency (see Chap. 2, Sect. 2.4). The potential reduction of CO_2 emissions in 2020 from both efficiency improvements and nonfossil sources is shown in Table 4.1 to be about 1.5 GtC/year, a reduction of 74% from the base case (the difference between the ER base case A and the high-efficiency case B). The relative potential of various nonfossil sources for substituting for fossil sources is also indicated in Table 4.1. The potential is in the vicinity of 40 quads, assuming that R&D makes nuclear power an expandable source once again and that it can triple by 2020. Nonfossil sources could be even greater with a breakthrough in solar R&D. The range of U.S. CO_2 emissions in 2020 could be from 0.5 to 2.1 GtC/year, depending on the effectiveness of efficiency improvement and the penetration of nonfossil sources. This compares to 1.36 GtC/year in 1987.*

For the year 2040, we have assumed for the high-efficiency case that no further improvements will occur in energy use efficiency beyond the large improvements assumed by Williams for 2020, although the mix of energy-using activities continues to evolve, as described by Williams. In other words, we presume that efficiency improvements will be harder and harder to make. The same may be true of energy sources. Nothing can grow without limit. As sources grow, they too run into barriers of one sort or another. It has occurred for coal with acid rain and for nuclear with safety and waste problems. Nevertheless, we think it is more likely that efficiency improvements will be limited before nonfossil sources.

Table 4.1 and Fig. 4.3 indicate that efficiency improvements and the use of nonfossil sources can reduce U.S. CO_2 emissions to about 0.5 GtC/year by 2040. If efficiency improvement is slower, as represented by the ER base case, then emissions are around 1.4 GtC/year, similar to the 1987 level. The reasoning and calculations behind Table 4.1 and Fig. 4.3 are given in Appendix C.

It should be emphasized that reducing U.S. CO_2 emissions over the next 50 years much below present levels would require ***both*** very large efficiency improvements ***and*** the aggressive deployment of nonfossil sources. One without the other will not be sufficient. Furthermore, much better nonfossil technology will be required in order for a transition away from fossil fuels to be possible at reasonable costs. Much more efficient end-use and conversion technologies that are also economic at relatively low fuel prices are also needed, and some such technologies exist already. The need would be to create the conditions necessary to promote their use—for example, by policies such as those proposed recently by the American Association for an Energy Efficient Economy (Chandler et al., 1988).

As difficult as it would be for the United States to make the transition away from fossil fuels, it would be even harder for much of the rest of the

*Calculated with the coefficients shown in note of Table 4.1. If calculated with the coefficients of Marland and Rotty (1983), which allow for nonfuel uses of oil and gas, the U.S. CO_2 emissions in 1987 are estimated to be 1.30 GtC/year.

Table 4.1. Potential reduction in U.S. CO_2 emissions via efficiency improvement and/or nonfossil energy sources assuming energy technology R & D successes

	1987	2020				2040				
	Actual	Base case[a]		High efficiency[b]		Base case[a]		High efficiency[b]		
		A[c]	B[d]	A[c]	B[d]	A[c]	B[d]	A[c]	B[d]	B′[e]
ELECTRICITY GENERATION, 10^9 kWh(e)										
Oil	119	500	500	120	220	800	400	120	0	0
Gas	273	800	800	450	450	1200	800	480	0	0
Coal	1464	3521	2421	1200	0	4627	1097	2272	0	0
Subtotal	1855	4821	3721	1770	670	6627	2297	2872	0	0
Nuclear	455	500	1500	500	1500	170	4000	170	2710	4000
Hydro	250	475	475	475	475	475	475	475	475	475
Solar, etc.	12	25	125	25	125	25	525	25	357	525
Subtotal	717	1000	2100	1000	2100	670	5000	670	3542	5000
TOTAL	2572	5821	5821	2770	2770	7297	7297	3542	3542	5000
PRIMARY ENERGY USE, quads										
Oil—Electric	1.26	4.9	4.9	1.2	2.2	7.8	3.9	1.2	0	0
Non-electric	31.38	31.6	21.6	14.8	10.7	31.3	21.3	21.8	14.0	7.3
Total	32.64	36.5	26.5	16.0	12.8	39.1	25.2	23.0	14.0	7.3
Gas—Electric	2.94	7.8	7.8	4.4	4.4	11.7	7.8	4.7	0	0
Non-electric	14.23	13.0	13.0	12.6	8.6	13.5	13.5	16.2	14.0	10.0
Total	17.17	20.8	20.8	17.0	13.0	25.2	21.3	20.9	14.0	10.0
Coal—Electric	15.19	34.3	23.6	11.7	0	45.1	10.7	22.2	0	0
Non-electric	2.83	6.9	6.9	4.9	3.0	12.2	12.2	3.0	3.0	3.0
Total	18.02	41.2	30.5	16.6	3.0	57.3	22.9	25.2	3.0	3.0
Total fossil	67.83	98.4	77.7	49.6	28.8	121.6	69.4	69.0	31.0	20.3
Biomass (non-electric)	0	0	20.0	0	20.0	0	20.0	0	20.0	20.0
Nuclear	4.92	5.3	16.0	5.3	16.0	1.8	42.7	1.8	28.9	42.7
Hydro	3.01	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
Solar, wind, geothermal	0.25	0.2	1.2	0.2	1.2	0.2	5.1	0.2	3.5	5.1
Total nonfossil	8.18	10.2	41.9	10.2	41.9	6.7	72.4	6.7	57.0	72.4
TOTAL PRIMARY ENERGY	76.01	108.6	119.6	59.8	70.7	128.3	141.8	75.7	88.0	92.7
CO_2 EMISSIONS,[f] GtC/year										
Oil	0.65	0.73	0.53	0.32	0.26	0.78	0.50	0.46	0.28	0.15
Gas	0.26	0.31	0.31	0.26	0.20	0.38	0.32	0.31	0.21	0.15
Coal	0.45	1.03	0.76	0.41	0.08	1.43	0.57	0.63	0.08	0.08
TOTAL	1.36	2.07	1.60	0.99	0.53	2.59	1.40	1.40	0.57	0.37
TOTAL CO_2 FROM ELECTRICITY GENERATION, GtC/year	0.45	1.07	0.80	0.38	0.11	1.46	0.46	0.65	0	0

[a] "Base case" refers to Edmonds-Reilly Model Base Case, as discussed in Chap 2.

[b] "High efficiency" refers to a high-efficiency scenario based on R. H. Williams 1987.

[c] Cases in "A" have limited contributions from nonfossil sources (e.g., no new nuclear reactors are ordered).

[d] Cases in "B" have the same fuel and electricity requirements as those in "A" but with assumed larger contributions from nonfossil sources, as described in Appendix C.

[e] "B′" involves additional electrification in the residential, commercial, and transportation sectors to exploit fully the assumed potential contribution of nonfossil sources of electricity.

[f] Coefficients used in calculating CO_2 emissions: 0.020 GtC/quad for oil, 0.015 for gas, 0.025 for coal (see text). (1 GtC = 1×10^{15} grams of carbon contained in CO_2.)

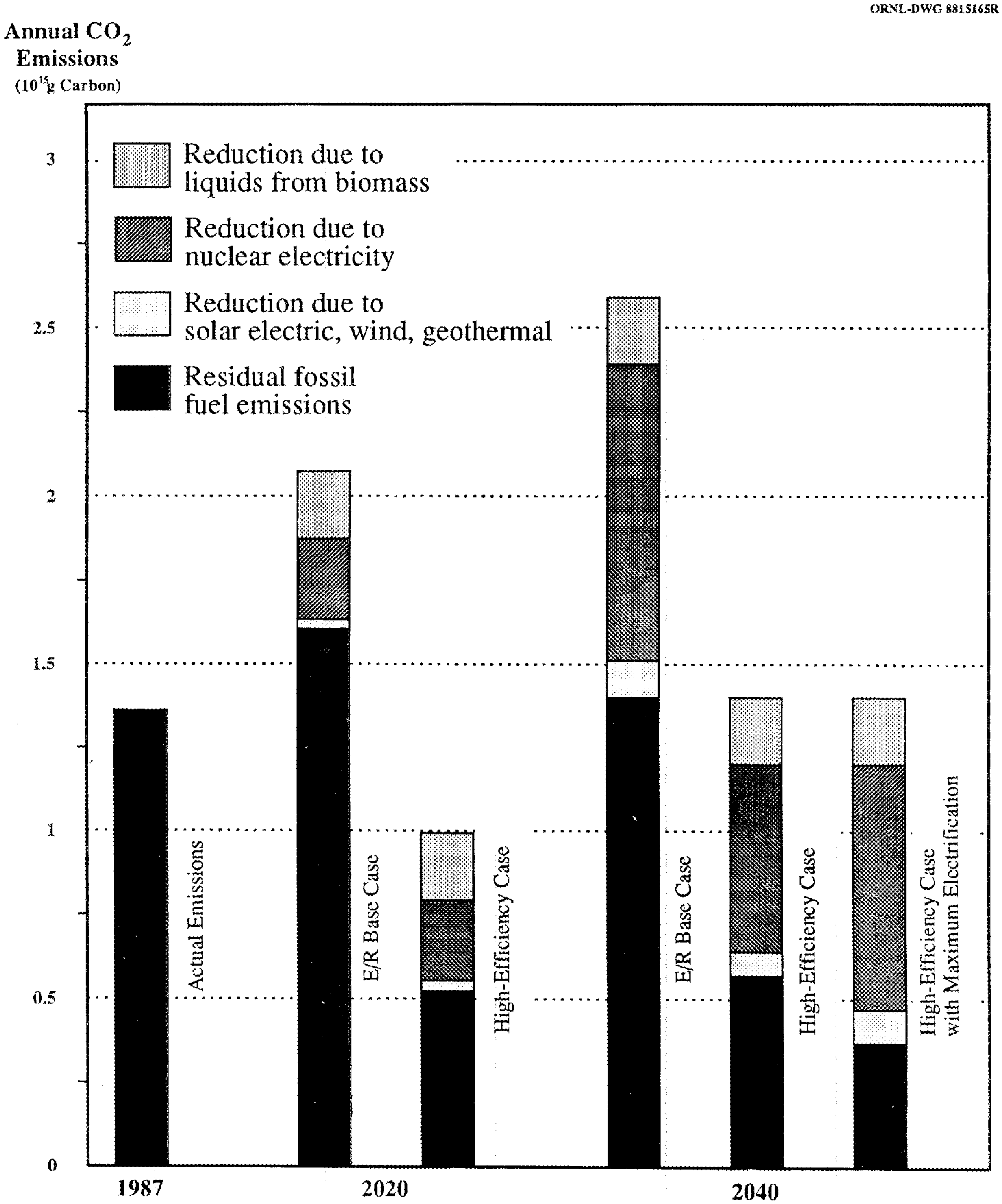

Fig. 4.3. Estimated potential of efficiency increases and nonfossil energy sources for reducing U.S. CO_2 emissions from fossil fuel combustion. The top of the bar indicates CO_2 emissions with limited contribution of nonfossil fuels, as enumerated in Table 4.1. The lower, black portion of the bar indicates the reduced CO_2 emissions made possible by R&D on nonfossil sources. The upper three sectors indicate the contributions of various nonfossil energy sources to the reduction in CO_2 emissions.

world, especially the developing world. Fossil fuel use by developing countries is growing so rapidly that if present trends continue CO_2 emissions by the developing nations will exceed those of the OECD countries by about 2005, as shown in Fig. 4.4.

Nevertheless, the steps needed in developing countries are similar to ones for the United States. The first action is to use fuel more efficiently and economically. As Goldemberg et al. (1988) document, this could also be the least cost approach to economic growth. Nonfossil sources are a more difficult problem because of their generally higher cost. R&D in the United States and elsewhere in the industrialized world to develop and improve nonfossil sources should be carefully planned to provide useful technologies for the developing world as well. R&D options which may be particularly useful for developing nations are indicated by the plus signs in the last column of Table 3.3, but additional R&D may be needed which is tailored to specific needs of particular countries.

As pointed out in Chap. 2, after Firor (1988) and Perry (1984), for any given concentration of CO_2 in the atmosphere, there may exist an allowable nonzero rate of CO_2 emission that will sustain the atmospheric concentration without increasing it. Thus, there is in effect a "fossil fuel ration" for the world. This ration, which might change with time, may be sufficient to drive the transportation system for the world (if that system is very efficient). It could also supply industrial needs including feedstocks for which substitutes are expensive. Research to establish what this ration may be is crucially important.

As discussed in Sect. 2.5.1.1, removal of CO_2 from the stack gases of central-station power plants and sequestering it, for example, in the oceans, would eliminate some of the climate impact of fossil fuel use and would increase the fossil fuel ration.

A fossil fuel ration notwithstanding, Circumstance 3 would likely lead to a much more highly electrified world. That is our current trend anyway, but it would be accelerated under Circumstance 3 because all the nonfossil sources (except biomass) tend to be electric. Electricity would tend to be the energy carrier of choice, but with some biomass and fossil-derived liquids and gases, and perhaps hydrogen, also contributing.

4.2 PROBLEMS, FUTURE CIRCUMSTANCES, AND A BALANCED STRATEGY

From a consideration of these three future circumstances and the four problem areas identified in Chap. 2, we establish the needs of a balanced R&D strategy. What we find is that the promising R&D options identified in Chap. 3 can contribute to meeting many of these needs.

The three future circumstances lead to the conclusion that a broad R&D strategy is necessary. It must include work to develop

1. more efficient end-use, fuel-switching, and conversion technologies (all circumstances);
2. technologies which extend oil and gas resources and improve the availability, flexibility, (e.g., conversion of coal and biomass to gases and liquids and of natural gas to liquids), and environmental acceptability of indigenous fossil resources (Circumstance 2 particularly); and
3. technologies that improve nonfossil sources (Circumstances 2 and 3 particularly).

Within this broad strategy, further specificity is needed to ensure that the four energy system problem areas identified in Chap. 2 are adequately addressed. These are (1) a variety of environmental, health, and safety issues; (2) energy insecurity and the instability of oil prices; (3) the energy needs of developing nations; and (4) problems with nuclear power.

That a balanced R&D strategy must be broad is perhaps obvious, but it is important nevertheless. A prudent R&D strategy for the nation is one which focuses both on the diverse range of end uses and on a variety of energy sources, both fossil and nonfossil. A comprehensive strategy is needed in part because of uncertainty: uncertainty about future energy demand, about the consequences of the greenhouse effect, and about the future pace of technological advance.

From our bottom-up examination of the state of the technology, we identified promising R&D options all across the energy system. Taken together, these options constitute a broad R&D agenda. Advances in crosscutting areas of science and technology enrich these options, and increase our optimism that R&D will be successful. But it still

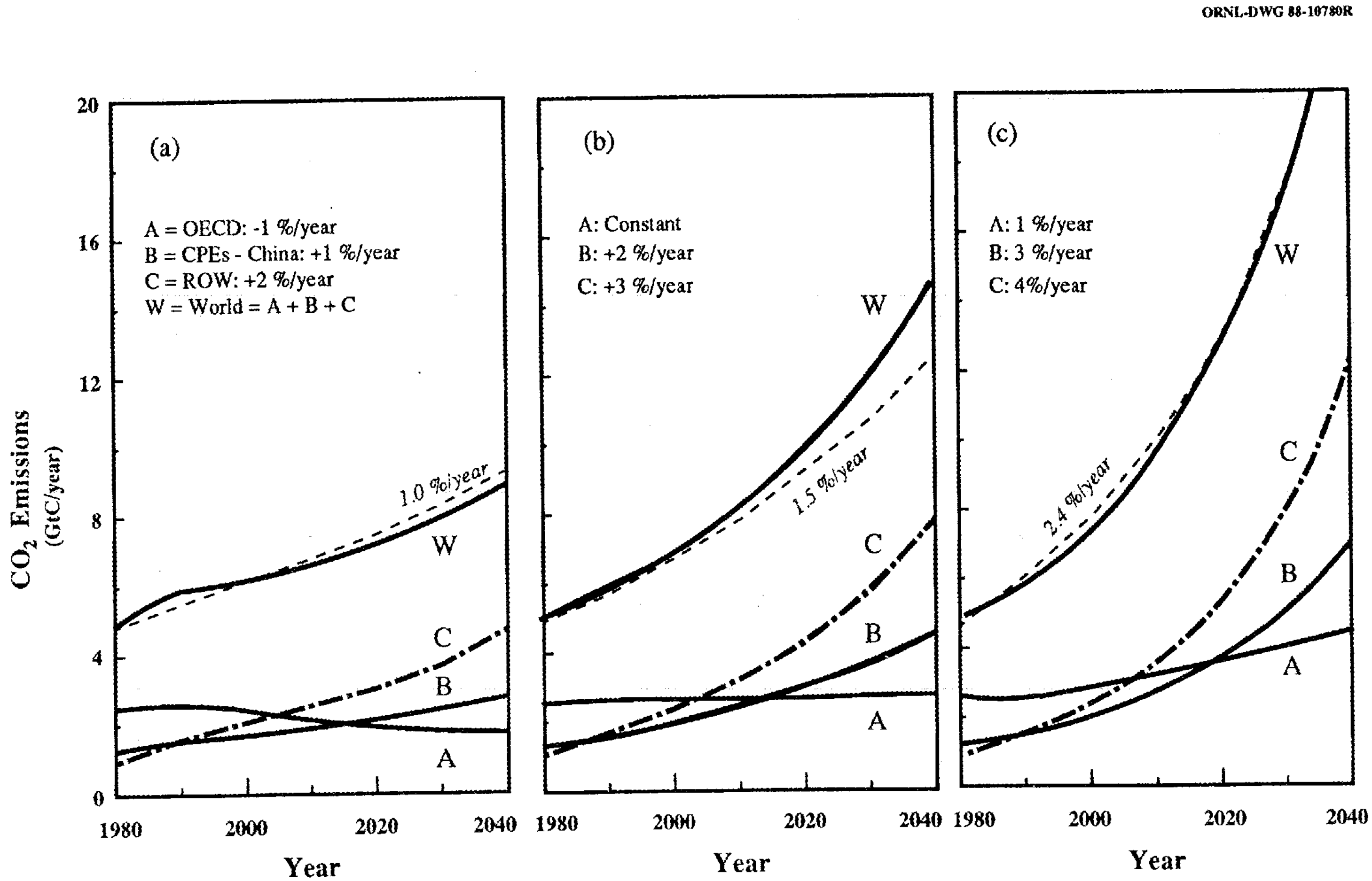

Fig. 4.4. Projected CO$_2$ emissions for various nation groups assuming various growth rates. These rates represent a range around recent trends. OECD = Organization for Economic Cooperation and Development; CPEs = centrally planned economies of USSR and Eastern Europe minus China; ROW = rest of the world, including China. See Appendix C, Table C-1.

remains to be shown that these promising R&D options are responsive to all the needs posed by existing problems and by our three future circumstances.

4.2.1 R&D Options and Energy System Problems

4.2.1.1 Environment, health, and safety issues

In Sect. 2.5.1, we discussed a whole series of environment, health, and safety issues that are related to the energy system. A number of the promising energy technology R&D options can contribute to resolving these issues. Although we find that our 50 options can contribute significantly to the solution of environment, health, and safety problems, they do not necessarily constitute a comprehensive set for each problem. For example, the problems with the coal fuel cycle are being addressed comprehensively by the Clean Coal Initiative. Some of our options are among the technologies being developed under that initiative but there are others as well. In this regard, therefore, our bottom-up options are not sufficient to do all that may be required for using coal more cleanly.

In the following list we indicate the relevance of our selected R&D options to the energy systems environment, health, and safety problems that were discussed in Chap. 2.

1. *The greenhouse effect:* Since this is the basis for circumstance 3, its relevance to R&D options will be discussed below; however, Table 3.3 indicates which R&D options would tend to reduce CO_2 emissions and those which might do the opposite.
2. *Stratospheric ozone:* Substitutes for chlorofluorocarbons used in heat pumps, refrigerators and air conditioners and in the blowing of plastic foam insulations is part of R&D associated with ***advanced heat pumps*** and ***building envelopes***. This R&D will also contribute to reducing the greenhouse effect.
3. *Nuclear accidents and proliferation of fissionable materials:* The safety issue is an objective of R&D on ***improving LWR technology,*** on the passively safe ***modular high-temperature gas-cooled reactor*** (MHTGR), and on the ***liquid metal fast breeder reactor*** (LMFBR). Proliferation is not amenable to any known technological fix (although technological innovations can help), but implementing safeguards depends on multilateral agreements.
4. *Acid rain:* Decreasing the pollutant sources of acid rain is the objective of the national effort on clean coal technologies. The options of ***fluidized-bed combustion*** and ***gasification*** are part of these technologies, as are more efficient electricity generation technologies, some of which may substitute (clean) natural gas for coal or may use gas derived from coal (i.e., ***aeroderivative turbines***, the ***Kalina cycle***, and ***fuel cells***).
5. *Health and safety of various fuel cycles:* With the exception of nuclear reactor safety already mentioned, no other R&D options were selected which improve the safety of other fuel cycles. Of course, the health issues associated with coal combustion are addressed by the same clean coal R&D options mentioned under acid rain. ***Waste management*** for the nuclear fuel cycle is an important option for ensuring public health with respect to nuclear power. It may be significant for other technologies as well, including coal and petroleum refining residues and wastes from the manufacturer of photovoltaic cells.
6. *Smog and CO:* High levels of smog and CO result primarily from vehicle emissions in urban areas under adverse meteorological conditions. Alternate fuels such as methanol, compressed natural gas, or electricity may be the only answers in some cities. R&D options potentially significant for these problems are ***advanced engine technologies*** which are more efficient and fuel flexible, ***automated dynamic traffic control***; the electric vehicle (which depends on ***advanced batteries***) and alcohol fuels derived from coal or biomass via ***gasification, liquefaction,*** or ***bioprocessing***.
7. *Land and water resource conflicts:* These are generally reduced by R&D options that improve the efficiency of energy services. Competition for land and water resources may pose obstacles for any energy source, especially for some solar technologies. Land use impacts from associated use of fertilizers and pesticides and from erosion of soil represent a challenge for biomass ***feedstock development*** R&D, but no different than for agriculture in general. High-temperature

superconducting transmission lines may provide some relief to power transmission corridor problems since much more power can be transmitted using existing corridors.

8. *NIMBY:* The Not-in-My-Back-Yard attitude toward some technologies is related to the land and water resources conflicts. Passively safe reactors such as ***MHTGR***, clean coal technologies, better waste management technology, and better ***municipal solid waste processing*** may contribute to softening of some of the NIMBY problems.
9. ***Indoor air pollution and safety of building energy systems:*** A potential problem with high-efficiency, tight buildings is indoor air pollution. It is one focus in the design of ***envelopes***, particularly foundations, which can reduce the source of radon, for example; and it can also be mitigated using ***smart sensors for control***, recuperated ventilation, and ***efficient heat pumps***. It would be one factor which needs to be considered when applying ***computer-assisted design techniques***. The safety of building energy systems, both gas and electric, may be greatly enhanced by smart sensors and controls (e.g., the so-called "smart house" wiring and gas plumbing system).
10. ***Automobile safety:*** The connection between automobile efficiency and highway safety needs further investigation, as indicated in Sect. 2.5.1.5. This is a potentially serious problem to be overcome in the development of more efficient vehicles. One key could be in the crosscutting area of high-strength, lightweight materials.

4.2.1.2 Energy insecurity and price fluctuations

As was pointed out in Chap. 2, to the extent that energy insecurity is measured in terms of the fraction of oil we import, R&D will generally play an indirect role. There is just too much oil in the Middle East that can be produced more inexpensively than any domestic supply—conventional, unconventional or synthetic. Other government policies may be required (DOE 1987e). However, R&D can yield technologies that can reduce oil or gas use, increase domestic oil and gas resources, and provide substitutes from coal and biomass. Table 3.3 indicates a significant number of these R&D options which can be identified by scanning the two columns under security (i.e., oil imports and fuel flexibility).

4.2.1.3 Energy needs of less-developed countries

Table 3.3 indicates that many R&D options could result in technologies judged to be useful to less-developed countries. Although there are many interesting possibilities, R&D aimed at the needs of specific countries may be required to refine or modify technologies useful in the United States to conditions of other countries or to develop totally different ones since infrastructures are so different. As we point out in Sect. 4.2.3, research on the energy systems in less-developed countries is in the best interest of the United States because it may provide options to minimize the greenhouse effect. Such R&D could also help less-developed countries cope with oil insecurity and price fluctuations; and to the extent the R&D is successful and improved technologies are used, the stress on oil markets could be lessened, benefitting all countries. Finally, technologies tailored for developing countries could provide a significant export trade.

4.2.1.4 Problems with nuclear power

The nuclear panel recommended a national R&D strategy for coping with this problem, which is summarized in Chap. 3, so we mention only the principal elements here. The promising R&D options for nuclear fission listed in Table 3.2 derive from that strategy. The first step is to improve the performance of operating nuclear power plants and to develop an advanced light water reactor (ALWR) that has passive safety features and is more forgiving than the present reactors. The second step is to develop a ***modular high-temperature gas-cooled reactor*** exhibiting walk-away passive safety protection which can be factory constructed, can supply high-temperature process heat, and will have high efficiency in electricity production. Such a reactor should be attractive to developing nations. Other reactor concepts exhibiting walk-away passive safety are being investigated, but our choice is MHTGR. The third step is to develop resource extension technologies, including a ***liquid metal fuel breeder reactor*** with passive safety features. Finally, the R&D program should resolve remaining issues in develop-

ing acceptable *waste disposal methods*. All of these options should be accompanied by R&D efforts to better understand the conditions of public acceptance and to find ways of involving representatives of constituencies with various points of view in decision making.

4.2.1.5 Summary: Problems and Options

In summary, we find that our promising R&D options can contribute significantly to resolving all four energy system problems, a not-too-surprising result considering how we chose the options in the first place. What about the requirements of future circumstances?

4.2.2. Future Circumstances and R&D Options

Table 4.2 indicates our judgment of the relative potential importance of the R&D options for coping with or achieving the three circumstances. The basis for the judgment is the rating rules given at the end of Table 4.2. These rules apply the evaluations given in Table 3.3 according to the needs of each future circumstance. The first observation in looking at Table 4.2 is that improved end-use technologies can be relatively important in all three circumstances. The importance of options tends to be similar between Circumstance 1 and 2 except that energy cost is a discriminator. In Circumstance 1, we expect the relatively low demand for primary energy will keep energy costs down, which reduces the urgency for R&D on options which are judged to be competitive only at relatively high energy costs. Higher costs are more likely in Circumstance 2.

For Circumstance 3, efficiency improvement R&D options and R&D on improving and developing nonfossil sources are of highest importance, of course, and fossil R&D options are rated L for low importance, except for some natural-gas-related options. In the near term, efficiency improvements and substituting gas for coal are potentially effective steps to reducing CO_2 emissions, as we have discussed. Hence, efforts to extend gas resources and use fossil fuels, especially gas, more efficiently have importance in Circumstance 3.

From Table 4.2, we conclude that our promising options can be very important for providing alternatives for coping with or achieving the three future energy system circumstances. Furthermore, all of the options are judged to have at least medium importance for one or the other of the three circumstances.

If Circumstance 3 were to occur, all nonfossil sources would be investigated actively. Notably missing from the list in Table 3.3 is geothermal in its various forms except that the geopressure resource is among the unconventional sources of natural gas. Unfortunately, much of the best geothermal resource is located in the western United States and is generally remote from major load centers. Circumstance 3 would make R&D to find and develop significant and economically suitable hot dry rock and magma formations relatively more important.

Similarly, R&D on the production, storage, and transport of hydrogen would be more important. Recently, the possibilities for the use of hydrogen as an energy carrier associated with large-scale deployment of photovoltaics in the desert Southwest have been evaluated (Ogden and Williams 1989). Hydrogen produced by electrolytic decomposition of water provides a compatible storage medium and can be pumped by pipeline around the country at relatively low costs, comparable to natural gas. Electrolytic hydrogen is, of course, a competitor to advanced batteries for electrifying vehicles. The key to such a possibility is a very inexpensive photovoltaic device which is, of course, one of the high-priority technologies for Circumstance 3.

4.2.3 New Opportunities

The final requirement of a balanced R&D strategy is that it provide new opportunities. This can occur serendipitously (e.g., during the course of research directed at one technology, discoveries lead to a new option). But new opportunities come also from basic or generic research in relevant areas of science and crosscutting technologies.

Thus, the commitment to including high-risk generic work in a balanced energy R&D strategy (a commitment we take as fundamental) reflects an act of faith sometimes said to be the "Faraday Rule." It flows from a popular story about Michael Faraday and a British prime minister. When Faraday was introduced, the prime minister asked him about the utility of his work on electricity. Faraday is said to

Table 4.2. Relative importance of promising R&D options for coping with or achieving the three future circumstances

R&D options	Energy significance: Near term	Energy significance: Long term	Energy significance: Ultimate potential	Energy cost	CO_2	Oil imports	Future circumstances[a]: 1	Future circumstances[a]: 2	Future circumstances[a]: 3
Improving efficiency of end use and conversion technologies									
Transportation efficiency									
Advanced engine technologies	M	H	L	0	+	++	M	H	H
Continuously variable transmission	M	M	L	0	+	++	M	M	M
Improved aircraft efficiency	M	M	L	+	+	++	M	M	M
Automated dynamic traffic control	L	M	L	+	+	+	M	M	M
Building efficiency									
Heat pumps	M	H	L	+	+	+	H	H	H
Lighting	M	M	L	+	+	+	M	M	M
Smart systems—sensors and controls	M	H	L	+	+	+	H	H	H
Envelopes	M	H	L	+	+	+	H	H	H
Factory-constructed components and buildings	L	M	L	+	+	+	M	M	M
Computer-assisted design	L	M	L	+	+	+	M	M	M
Existing building retrofits	H	H	L	+	+	+	H	H	H
Industry efficiency									
Catalysts	M	M	L	+	+	+	M	M	M
Sensors and controls	H	H	L	+	+	+	H	H	H
Separations	M	M	L	0	+	+	L	M	M
Advanced heat management	H	H	L	+	+	+	H	H	H
Cogeneration	H	M	L	+	+	+	H	H	M
Steel processes	M	L	L	+	+	0	M	M	L
Pulp and paper processes	M	M	L	+	+	+	M	M	M
Agricultural techniques	M	M	L	+	+	+	M	M	M
Electricity applications									
Superconducting applications	L	M	L	−	+	0	L	M	M
Power electronics	M	M	L	+	+	+	M	M	M

Table 4.2. *(continued)*

R&D options	Energy significance: Near term	Energy significance: Long term	Energy significance: Ultimate potential	Energy cost	CO_2	Oil imports	Future circumstances[a]: 1	Future circumstances[a]: 2	Future circumstances[a]: 3
Improving efficiency of end use and conversion technologies *(continued)*									
Advanced conversion									
Aeroderivative gas turbines	M	H	H	+	+	+	H	H	H
High-temperature Brayton cycle (MHTGR)	L	H	H	+	+	+	H	H	H
Kalina cycle	L	M	H	0	+	+	L	M	M
Fuel cells	M	M	H	0	+	+	M	M	M
Hot gas cleanup	L	H	H	0	0	0	M	H	L
Storage									
Advanced batteries	L	M	H	−	+	+	L	M	M
Thermal storage	L	M	H	0	+	+	L	M	M
Improving fossil sources									
Oil									
Enhanced oil recovery	H	M	L	0	0	++	M	H	L
Field characterization techniques	H	M	L	0	0	++	M	H	L
Gas									
Exploration and drilling techniques	H	M	L	0	0	++	M	H	L
Unconventional gas techniques	H	H	L	0	0	++	M	H	M
Coal									
Oil substitutes	M	M	L	+	−	+	M	M	L
Fluidized-bed combustion	M	H	H	+	0	+	H	H	L
Bioprocessing	L	M	H	−	−	+	L	M	L
Gasification	M	H	H	0	−	+	M	H	L
Liquefaction	L	H	H	−	−	++	M	H	L

Table 4.2. *(continued)*

R&D options	Energy significance: Near term	Long term	Ultimate potential	Energy cost	CO_2	Oil imports	Future circumstances[a]: 1	2	3
Improving nonfossil sources									
Nuclear fission									
Improving LWR technology	H	H	L	+	+	+	H	H	H
MHTGR	L	H	L	+	+	+	H	H	H
Liquid metal fast breeder reactor	L	M	H	−	+	0	L	M	M
Waste management techniques	H	H	H	+	0	0	H	H	H
Biomass									
Feedstock development	M	H	L	0	+	++	M	H	H
Conversion technology	M	H	L	0	+	++	M	H	H
Municipal solid waste processing	M	M	L	+	0	0	M	M	L
Solar electric									
Photovoltaic	L	M	H	−	+	+	L	M	M
Solar thermal	L	M	H	−	+	+	L	M	M
Hydroelectric	M	M	L	+	+	+	M	M	M
Wind turbines	L	M	L	0	+	+	L	M	M
Fusion									
Reactor systems	L	L	H	0	+	0	L	M	M
Breeder	L	L	H	0	+	0	L	M	M

[a]Circumstance 1—High efficiency, low oil use

Circumstance 2—Significantly more rapid increase in primary energy demand, particularly oil and gas, than for Circumstance 1.

Circumstance 3—Fossil fuel use is curtailed because of greenhouse effect.

Rules for Table 4.2

Circumstance 1

L	Option does not increase efficiency or reduce oil use relative to present technology
M	Option has an M for either near-term or longer-term energy significance or an H for ultimate potential, and the option can increase efficiency or reduce oil use.
H	Option has an H for either near term or longer term energy significance and it can increase efficiency or reduce oil use.

General rule for Circumstance 1: Drop one grade for an option if energy cost is rated "0" or "-".

Circumstance 2

L	Option does not increase oil or gas resources or reduce oil or gas use and does not have H for either near- or longer-term energy significance
M	Option can increase oil or gas supply or reduce oil or gas use and has M for either near- or longer-term energy significance, or the option can increase other primary supplies and has an M or H for near-term or an H for longer-term energy significance or ultimate potential.
H	Option can increase oil or gas supply or reduce oil or gas use, and it has an H for either near- or longer-term energy significance, or it increases other primary supplies and has an H for near-term energy significance.

Circumstance 3

L	Option does not reduce CO_2 relative to displaced technology.
M	Option can reduce CO_2, and it has an H for near-term or an M for longer-term energy significance or an H for ultimate potential.
H	Option can reduce CO_2, and it has an H for longer-term energy significance.

NOTE: L means the R&D option may have less importance; M means medium importance, and H means high importance for coping with or achieving the future circumstance.

have responded, "I know not what the use of my work will be, but someday you will tax it."

Our review of these crosscutting areas, as documented in Vol. 2 and discussed briefly in Chap. 3, revealed a variety of technological options which influenced our optimism about some areas of energy technology R&D. This was true in the areas of materials science, biotechnology, and microelectronics and computing especially. Examples include bioprocessing of coal and biomass; smart sensors for buildings, industrial processes, and down hole diagnostics for oil/gas exploration and production; and ceramics for high-temperature turbines and other heat engines. DOE, EPRI, and GRI all devote considerable resources to crosscutting areas of science and technology. Little attention, however, is being given to the area of decision making and management. Many of the problems facing the energy system involve situations in which there is public opposition or concern. It is often said that management of nuclear wastes is a social, not a technical problem. Transnational decision making is a growing need because of global environmental problems. Many energy facilities have sufficient noxious aspects that they evoke NIMBY. Despite the need and a growing body of relevant social science, very little basic or generic research on decision-making is sponsored by DOE, EPRI, or GRI.

4.2.4 Balancing the current R&D agenda

Since all of our promising R&D options and many others are being worked on to some degree through public or private sector support, we conclude that the national R&D effort is suitably broad. The pluralistic set of institutions which compose the energy R&D system of the country is indeed conducting R&D which is responsive to the uncertain future and to most of the problems facing the energy system. In addition, the areas of crosscutting science and technology described in Sect. 3.2 are being pursued actively except perhaps the area of decision making and management. We found this conclusion to be quite striking, surprising, and comforting.

Although the national R&D effort is suitably broad, is it adequate? The combined energy technology budgets for DOE, the Nuclear Regulatory Commission, GRI, and EPRI amounted to about $2.8 billion for FY 1988. These budgets are shown in Table 4.3, where expenditures are broken down between end use and various sources. The combined expenditure for R&D is about 0.7% of the annual cost paid for energy ($376 billion per year in 1987). Furthermore, the energy technology budget has been declining for years, and today it stands at one-half of its value a decade ago in constant dollars. The record of the past 10 years is plotted in Fig. 4.5. The percentages spent on end-use technology and the various sources are shown in Fig. 4.6. For such a vital part of the economy, the combined expenditure for R&D seems low, even if one assumes that other private sector R&D investment is also of about the same magnitude. We have no absolute scale on which to judge, however, except to ask whether we are doing the research necessary to solve system problems and to provide options for future circumstances.

From the discussion in Sect. 4.1, we conclude that we are **not** ready to cope with Circumstance 3. Nonfossil sources, including nuclear power, are just not yet good enough. From this point of view, the nation's R&D agenda is neither adequate nor balanced. A much greater effort is needed to develop and improve nonfossil sources and to improve the efficiency and economics of end-use technologies. The latter has the greatest potential in the short- to mid-term. Furthermore, the adoption of high-efficiency technology will provide more time to develop better nonfossil sources.

We cannot predict when the greenhouse effect will drive energy policy. It may be starting now, but even if it is not, it seems likely that it will eventually. Substantially higher CO_2 concentrations in the atmosphere may be acceptable; but at some level, which is likely to be reached within a few decades, further increases will likely be perceived as unacceptable. The R&D that will provide the options to decrease our reliance on fossil fuels requires some substantial lead time, and it seems imprudent to delay. Furthermore, what will we have lost by aggressive action now? We will have learned how to be more efficient at competitive costs, a highly desirable outcome no matter what the future circumstance. We have pointed out that Circumstance 1 is a desirable goal regardless of the greenhouse issue. We will also have learned how to make nuclear power even safer through greater reliance on

Table 4.3. Fiscal year 1988 energy technology R&D budgets: DOE, EPRI, GRI, and USNRC
(in millions of 1988 $)

R&D	DOE	EPRI	GRI	USNRC	Total	%
Efficiency	156.3	26.1	67.8		250.2	9.0
Renewable energy						
Solar	96.9	5.4				
Geothermal/Hydro	20.9	4.8				
Energy storage	29.8	6.9				
Total renewable	147.6	17.1			164.7	5.9
Civilian nuclear	347.0[a]	35.3		119.7[b]	502.0	18.1
Magnetic fusion	335.0[c]				335.0	12.1
Fossil fuel	327.0	77.7	29.4		434.1	
Clean coal	199.1				199.1	
Total fossil	526.1	77.7	29.4		633.2	22.8
Environment, health and safety	269.3[d]	73.7	12.4		355.4	
Basic energy sci.	437.2[e]		14.5		451.7	
Total EH&S/BES	706.5	73.7	26.9		807.1	29.1
Transmission/transport/distribution	[f]	33.6	14.5		48.1	1.7
R&D planning, mgmt., and exploratory research	[g]	11.5	25.7		37.2	1.3
TOTALS	2218.5	275.0	164.3	119.7	2777.5	100

[a]The DOE civilian nuclear budget includes funding for the Light Water Reactor program, Advanced Reactors R&D, Space and Defense Advanced Nuclear Power Systems, and Advanced Nuclear Facilities. It does not include remedial actions or waste technology funding ($252 million in FY 1988), nor does it include funding for AVLIS Atomic Vapor Laser Isotope Separation). In FY 1988, AVLIS was funded at $90 million.

[b]The USNRC budget is for regulatory research.

[c]Magnetic fusion for DOE does not include $150 million for inertial fusion R&D funded out of the Defense Programs.

[d]The DOE Environment, Safety, and Health budget includes funding for the Biological and Environmental Research Program.

[e]Basic Energy Sciences here include university research support, university research instrumentation, and energy research analysis as well as the DOE Basic Energy Sciences Program itself.

[f]For DOE, electricity transmission and distribution research is included in energy storage.

[g]Funding in this area is included with the other major DOE areas listed above.

Sources: The DOE budget is from summaries of the *House-Senate Conference Report*, which appeared in *Inside Energy*, Jan. 4, 1988; the EPRI budget is from the *Research and Development Program Plan, 1988–1990*; the GRI budget is from the *1989–1993 Research and Development Plan* and *1989 Research and Development Program*; and the USNRC budget is from the *Appendix to the Budget of the U.S. Government, 1980–1989*.

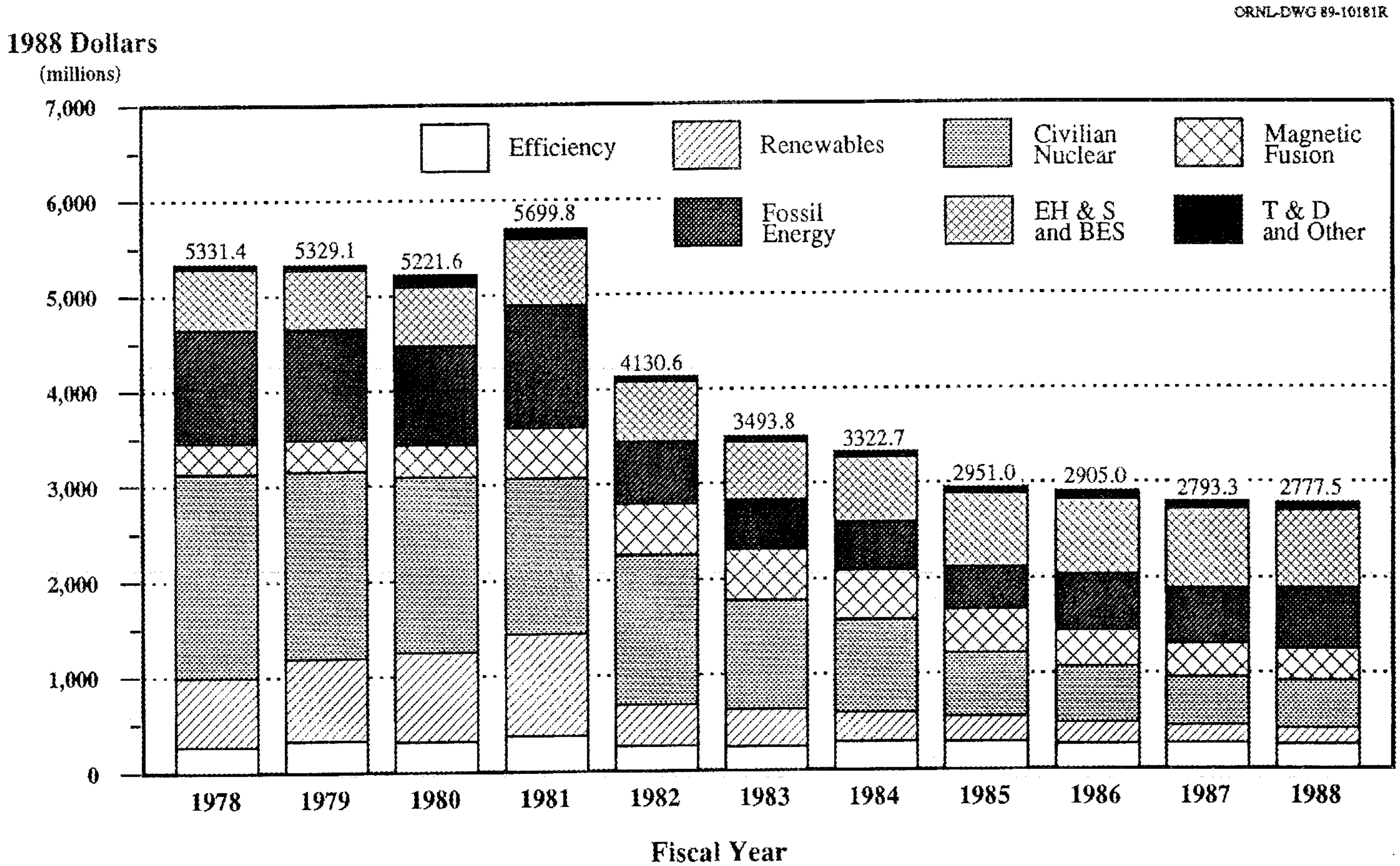

Fig. 4.5. Combined energy technology R&D budgets (DOE, EPRI, GRI, and USNRC), in millions of 1988 dollars, for efficiency improvement; various energy sources; environment, health, and safety (EH&S) research; basic energy sciences (BES); and "T&D and other." The latter includes GRI and EPRI funds for transmission, transportation, and distribution and planning and management functions. *Sources:* DOE, FY 1988, derived from summaries of the *House-Senate Conference Report on the DOE Budget*, which appeared in *Inside Energy*, Jan. 4, 1988. DOE, FYs 1978-87, *Appendix to the Budget of the U.S. Government, 1980-1989; Department of Energy Congressional Budget Request; Department of Energy Budget Highlights*; Department of Energy Budget Formulation Office, personal communication. EPRI, Annual Reports of the Electric Power Research Institute; and Research and Development Plans. GRI, Five-Year Research and Development Plans and Program; and Gas Research Institute Annual Reports. USNRC, *Appendix to the Budget of the U.S. Government, 1980-1989.*

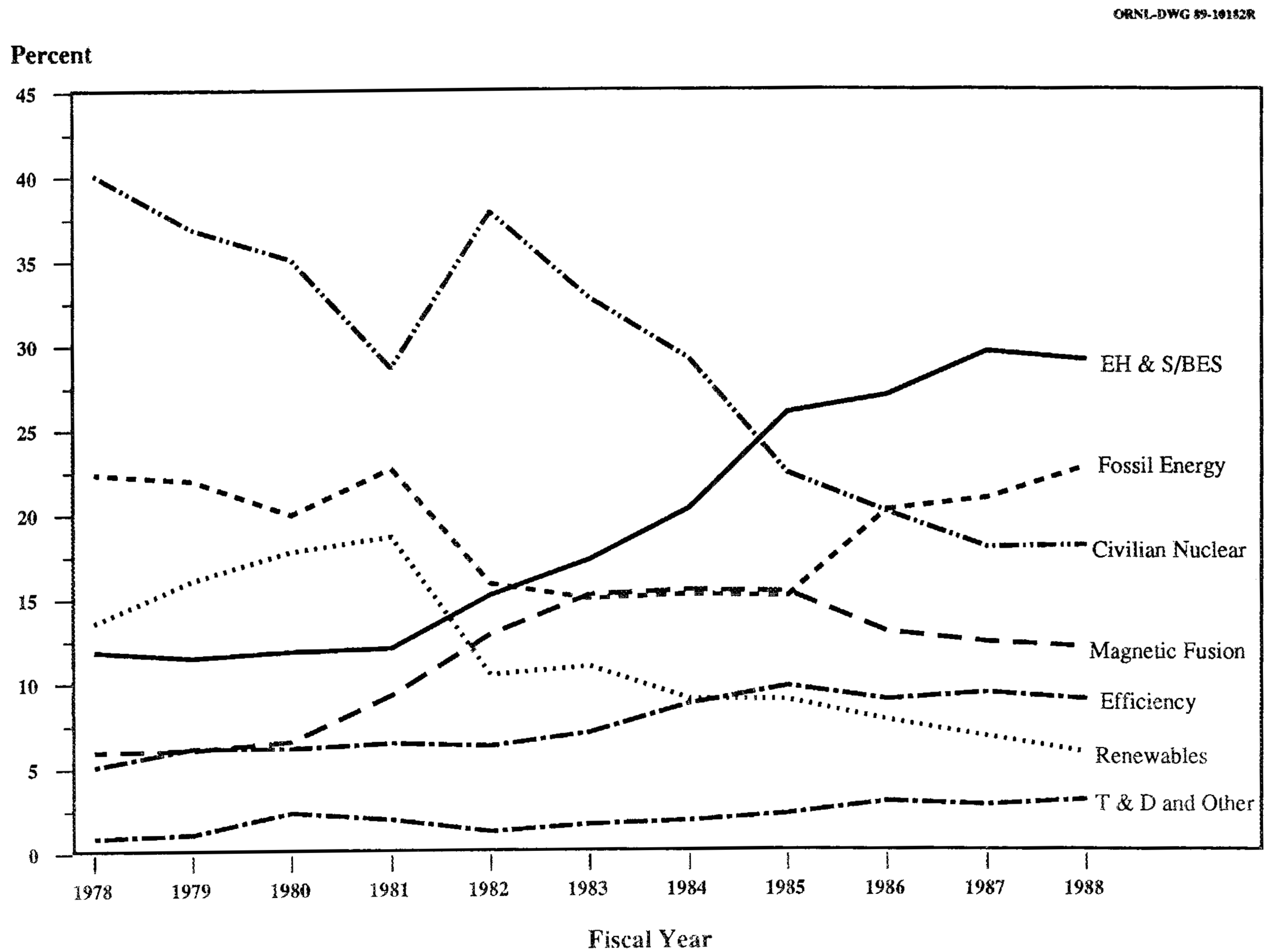

Fig. 4.6. Percentages of combined energy technology budgets (DOE, EPRI, GRI, and USNRC) for efficiency improvement; various energy sources; environment, health, and safety (EH&S) research; basic energy sciences (BES); and "T&D and other." The latter includes GRI and EPRI funds for transmission, transportation, and distribution and planning and management functions. Percentages derived from the data of Fig. 4.5.

passive safety features, and, one hopes, acceptable to the great majority of people. We will have learned how to make solar and other renewable sources more economically competitive. We will have accelerated determining the feasibility of fusion. These outcomes will be useful in any event, and the cost of achieving them on an accelerated schedule is the increased cost of R&D. What might this cost be?

To get an approximate number, we postulated expanding efforts on end-use and conversion efficiency, nuclear power, biomass, solar energy (and other renewables), and fusion. We also believe an R&D program aimed at improving efficiency and developing nonfossil sources in less-developed countries should be part of the package. We judge that efficiency and nuclear should have the highest priority, since their effects on reducing CO_2 can be large and purchased at reasonable cost. Some renewables can also help, particularly biomass which can be used to supply portable liquid and gaseous fuels, and fusion is an attractive longer-term possibility with a virtually unlimited resource base. Our judgment is that given the uncertainty about public acceptance of nuclear power and the uncertainties about the success of future R&D, all four areas should be pursued. Of course, relative progress between options should determine budget allocations, taking into account the fact that some are inherently more expensive to develop than others. Our estimates of the increased costs are as follows:

1. **Improve the efficiency and economics of end-use and conversion technologies.** We would argue that this area of R&D should not be budget limited so long as important options are yet to be explored. Our list of promising R&D options contains many opportunities. Many are also part of the DOE Multiyear Plan for conservation research (DOE 1988d) but are not included in congressional appropriations. We would propose a several-year, phased increase from the recent level of $250 million to perhaps twice that amount, which could be easily justified by the merits of options. The proposed National Energy Policy Act of 1988 (U.S. Congress 1988a) suggests a similar figure. An important part of the effort would be to evaluate and experiment with policy options which could stimulate the adoption of improved, more efficient technologies. ***Additional cost is about $300 million per year.***
2. **Improve nuclear power.** If the elements of the agenda suggested in Vol. 2 (Sect. 2.2) and outlined in Sect. 3.1.2.4 were followed, the additional big-ticket items (over and above the present level of funding) would be the prototyping of two reactor concepts over the next 10 years: an advanced LWR (ALWR) and the MHTGR.* Prototyping the liquid metal breeder (LMFBR) with passive safety features could be deferred until the first decade of the next century. ***Additional cost might be $3 billion to $4 billion over the next 10 years, or $300 million to $400 million per year on average.***
3. **Solar and other renewables.** We would suggest expanded budgets for biomass, hydroelectricity (to capture 50 GW remaining potential capacity), photovoltaics, solar thermal electricity, and others. We believe a phased increase over several years to twice the FY 1988 level is reasonable. ***Additional cost is about $170 million per year.***
4. **Fusion.** It is estimated that about $1 billion to $2 billion per year is currently expended worldwide on fusion power research. If this were well coordinated, it should be sufficient to establish technical and economic feasibility perhaps in 15 to 20 years.
5. **Technologies for less-developed countries.** Currently, the U.S. Agency for International Development spends about $200 million per year on energy problems in less-developed countries. If new technologies are to be developed and demonstrated adequately, a much larger effort is required. We estimate that the U.S. effort needs to be in the range of $300 million to $400 million per year. Again, the total effort needs to be shared with other industrialized nations. ***The additional annual cost is about $100 million to $200 million.***

*The recent decision by DOE to recommend an MHTGR as one of the new defense materials production reactors is important and positive. Cost sharing with other nations is also a possibility which should be explored.

Thus, a rough guess about the added R&D budget required to prepare adequately for Circumstance 3 would average about \$0.9 billion to \$1.1 billion per year over the next 10 years—less than a one-third increase of the energy technology R&D expenditures by the nation for FY 1988.

This additional R&D investment might be derived from both public and private contributions. A very small tax on fossil fuel use could raise the public sector portion. A tax rate of as little as 0.2% would raise about \$600 million per year. The private sector contribution could come from matching funds invested by private firms participating in the R&D. Their reward would be marketable improved technology.

The FY 1989 Energy and Water Appropriations bill (U.S. Congress 1988d) authorized a study by the National Academy of Sciences through DOE to look at the R&D requirements of Circumstance 3. That should lead to a much better estimate of what kind of extra R&D efforts the greenhouse effect may require.

4.3 SUMMARY

A balanced energy technology R&D strategy for the nation is one which addresses energy system problems, provides options for coping with future circumstances, and seeks new opportunities. To accomplish these goals, the R&D agenda must be broad, including work to develop and improve the efficiency and economics of end-use technologies and to develop and improve both fossil and nonfossil sources. The promising R&D options identified in Chap. 3 in aggregate are a broad set spanning the entire energy system. As a group, they are relevant to many of the energy system problems discussed in Chap. 2, and they also would provide options for the three future circumstances we considered.

Since all of these options and others are being worked on to varying degrees, we conclude that the existing national energy technology R&D agenda is sufficiently broad to be balanced. However, given the fundamental importance of energy to the economy, the current national R&D investment of public funds of about 0.7% of total expenditures for energy-sector investments, and perhaps twice that amount if private sector investments are taken into account, seems low. Furthermore, it is obviously inadequate for coping with Circumstance 3, the greenhouse effect.

It is our guess that the annual energy technology R&D budget of the nation would need to be increased by about \$1 billion to correct the inadequacy. This includes \$100 million to \$200 million for research on technologies that could be used to reduce CO_2 emissions by developing nations. Much more effort is needed to accelerate the development and improvement of nonfossil sources, none of which is presently ready to be substituted for fossil sources on a large scale. Nuclear power is the closest to being ready, but the present de facto moratorium on further expansion may persist unless better reactors are developed.

The best near- to mid-term chance of reducing CO_2 emissions is to generally improve the efficiency of energy use and conversion. This can be encouraged by the development of end-use technologies which are more efficient and less costly. It is clear, however, that CO_2 emissions cannot be substantially reduced from present levels without ***both*** improved efficiency ***and*** the aggressive use of nonfossil sources.

Chapter 5

Principal Conclusions and General Observations

During the final stages of this study, the synthesis team posed the following questions: "What are our most important conclusions about energy technology R&D, and what general observations do we have concerning the present state of the energy system?" Each of the observations represents a consensus view of the authors. A number of the observations go far beyond the study's specific focus on energy R&D, but we hope that these observations will have value to readers of this report as they think about the future of energy.

5.1 PRINCIPAL CONCLUSIONS

1. *The energy technology R&D effort of the country should be and is broad in scope.* Breadth is needed for two principal reasons. First, there are no perfect technologies for providing energy services. Some have a limited resource base (e.g., oil and gas); some may cause significant environmental damage (e.g., coal) or pose safety concerns (e.g., nuclear); some may be expensive (e.g., solar); and some may be difficult to deploy because they require action by many different people and institutions (e.g., efficiency). Second, large uncertainties about fossil fuels (i.e., about the rate of their use, particularly of oil and gas, and the greenhouse effect) suggest the need for a broadly based R&D agenda to provide a robust menu of better technology options.

   The significant areas of need and/or opportunity are receiving R&D attention. We are impressed that the polycentric (public-private sector) energy R&D system in the United States is addressing all the attractive options we identified and more. R&D progress across the spectrum of energy technology options and in related areas of science and crosscutting technologies makes us technology optimists.

2. *Although the R&D effort is broad, it is not sufficient to cope with the possible future circumstance that concern for the greenhouse effect will lead to limits on fossil fuel use.* None of the nonfossil energy sources is both competitive with fossil fuels and deployable at a scale sufficient to reduce CO_2 emissions. Nuclear power is nearest in cost, but it is not expandable without significant improvements; solar in its various forms is expensive or limited, and fusion is yet to be demonstrated. These considerations make the deployment of more energy efficient technologies the best near- to mid-term approach to reducing CO_2 emissions.

3. *The technical potential for economical improvements in the efficiency of energy use and conversion is very large and growing.* Technologies exist or are under development that could, if adopted, significantly reduce energy use for all sectors of the economy. To the extent that aggregate energy demand is reduced by the economic adoption of more efficient technologies, the resulting national outcomes would be desirable. Benefits would include reduced pressure on oil

and gas markets, increased energy security, enhanced competitiveness, reduced stress on the environment (including reducing the greenhouse effect), and increased time to develop better nonfossil energy sources. However, the rate and extent of adoption of more efficient and economical technologies depend on many factors and are highly uncertain.

4. *The R&D investment necessary to develop better nonfossil energy sources and to improve technologies for more efficient use and conversion of energy is the cost of insurance needed to protect against the possibility that fossil fuels will need to be curtailed because of concern about the changing greenhouse effect.* Paying our technological insurance premium will probably cost an additional $1 billion a year. Doing the necessary R&D will require some considerable lead time, and it seems imprudent to delay. Furthermore, the prospects appear bright for producing much improved technology. What will we have lost by aggressive action now? We will have learned how to be more efficient at competitive costs, to make nuclear power even safer through greater reliance on passive safety features, to make solar and other renewable sources more economical, and to accelerate determining the feasibility of fusion.

5. *Better technologies for developing nations can yield numerous benefits.* The rapid growth of demand for oil and other primary energy sources by many developing nations poses both problems and opportunities. The problems are oil market and global environmental stresses. Better technology tailored to the needs of each country may mitigate these pressures while stimulating economic growth. Additionally, the development of such technology may lead to mutually beneficial trade and represents, therefore, an important opportunity for the United States.

6. *Fossil fuels may still predominate in the U.S. and world energy systems 50 years hence unless concern about the greenhouse effect intervenes.* Fossil fuels, particularly oil and gas, are marvelous energy sources because they are easy to use at nearly any scale and they are portable and transportable. At present use rates, world conventional oil resources should last 60 years and gas 130 years, and unconventional sources are at least as large. Coal resources are many times greater. Thus, fossil fuels are very tough competitors, and only environmental considerations such as CO_2 or a major cost breakthrough by nonfossil technologies will cause the world to move from its reliance on fossil fuels in the next half century.

5.2 GENERAL OBSERVATIONS

1. *The U.S. energy system is relatively healthy.* This observation should not imply that the energy system is free of problems or that it can easily adapt to any future circumstance. In truth, many energy system problems are characterized by real differences of opinion among experts and are the foci of controversy among political-social-economic interests. Our optimistic observation flows from two facts: The problems are being worked on; and because the energy system has demonstrated resilience, we believe that resilience will characterize its future. Our only reservation is the greenhouse effect.

2. *Many important energy issues are international.* Energy prices are generally bounded by world oil prices, which in recent years have been heavily influenced by OPEC. It is instructive to recall that the decision which led to the recent recession in the U.S. oil industry was made in Saudi Arabia. Energy technology and R&D are part of an international market which makes new technologies rapidly available worldwide; and, in fact, R&D itself is increasingly being carried out in a cooperative international context. Some environmental impacts of energy technologies know no national boundaries. The threats to political and economic stability, especially evident in the less-developed countries, that may flow from energy problems hold dangers for all countries. The current debt crisis in the less-developed countries was exacerbated by the oil shocks of the 1970s.

3. *Oil security (dependable supplies and price stability) is predominantly a nontechnical issue.* The

location of the overwhelming portion of the world's oil reserves in the Middle East, and its low cost of production effectively precludes economically competitive domestic alternatives to imported oil. Thus, the maintenance or enhancement of domestic oil production or the development of synthetic substitutes for oil would require some system of government price supports (e.g., an import tax). Low-cost imported oil generally stimulates increased consumption and precludes development of domestic sources and use of more efficient end-use technologies.

4. *Environmental concerns will be a continuing and powerful factor influencing the energy system.* Environmental regulations are a permanent fixture in the energy system, and government at every level is organized to enforce those regulations. Public interest in the environment is well established. In truth, the U.S. public consistently has been ahead of political leaders in its demand for more stringent protection of the environment. The strong support for environmental protection in the United States is increasingly being manifested in countries around the world.

5. *Because fossil fuels will be used for many years (regardless of CO_2), domestic sources should be improved.* R&D to develop technologies that can use coal more cleanly and efficiently (or convert it to liquids or gas) and that extend oil and gas resources is an important strategy to help ensure energy security and cap fuel prices.

6. *A fossil fuel "ration" may exist for any given level of CO_2 in the atmosphere.* It may not be necessary to reduce fossil fuel use to zero to hold the CO_2 concentration in the atmosphere at a constant value. For any given concentration, there may exist an allowable, nonzero CO_2 emission rate that would not cause the CO_2 concentration to increase. This maximum emission rate, which might change with time, may be sufficiently large that the corresponding permitted fossil fuel use or "ration" is a significant energy source. At present, our tentative view is that such a "safe" level of CO_2 emissions might be roughly half the current worldwide rate (i.e., about 2 to 3 GtC/year). In any case, discovering what the "ration" might be should be a high-priority R&D objective.

7. *Sequestering CO_2 from fossil fuel sources seems impractical.* CO_2 can be scrubbed from the emissions of fixed sources such as fossil-fired central power stations and the CO_2 sequestered from the atmosphere by pumping it into the deep oceans, for example. The costs would be high, however, and possibly prohibitive (Steinberg, Cheng, and Horn 1984). Also, today the majority of the CO_2 from fossil fuel burning comes from mobile sources and numerous small stationary sources that are not well suited for separating and collecting CO_2. That is likely to be even more the case in the future since the large stationary sources are those most likely to be replaced by nonfossil sources. Alternatively, CO_2 can be stored in trees, as part of a massive reforestation effort (Marland 1988). The benefit would be temporary, however, since the new forests would eventually mature and cease to be a net sink for CO_2. Furthermore, the social problems with reversing land clearing trends are formidable.

8. *Discontinuities may characterize the greenhouse effect.* As greenhouse gases accumulate and global warming occurs, temporal discontinuities may arise. Examples might include freeing methane stored in clathrates as ocean temperatures rise or accelerated oxidation of peat due to both drying and higher air temperatures. Alternatively, methane may be produced due to increased anaerobic digestion of peat. Such potentially rapid positive feedback phenomena, as well as potential counteracting negative feedback mechanisms, need to be understood much better. It is crucially important to energy planning to know if there are irreversible thresholds or discontinuities in greenhouse phenomena.

9. *Both improved efficiency and increased use of nonfossil sources will be necessary if CO_2 emissions are to be reduced.* The United States (or any nation) will find it very difficult to reduce CO_2 emissions without incurring high costs.

Nonfossil substitutes are just not very competitive, or they cannot be expanded significantly due to physical constraints (e.g., hydropower) or social constraints (e.g., nuclear power). On the other hand, technologies for using energy more efficiently and economically are available across the economy and more are under development; as a result, improved efficiency is the first line of defense in controlling the greenhouse effect. It can provide the time needed to improve and develop nonfossil sources which must provide the longer-term solution. Only a combination of continued significant improvement in the efficiency of energy use and conversion, in concert with the rapid improvement, development, and deployment of nonfossil sources, is likely to yield a sustained reduction in CO_2 emissions. Implementing the combination will be costly without substantial R&D successes on both end use technologies and sources.

10. *The rate of penetration of more efficient technologies is uncertain.* Barriers to the adoption of more efficient technologies, such as imperfect consumer information, the tendency to make investments for lowest first cost rather than for lowest life cycle cost, uncertainties about future energy prices, and suspicions about the reliability and performance of new technologies, may all limit the penetration of more efficient technologies. A better understanding of the importance of these barriers and of the effectiveness and costs of government and utility actions to reduce them is needed if efficiency improvement is to be an effective tool for energy system stability, including reducing CO_2.

11. *The efficiency of electricity generation from fossil fuels has not improved for 25 years, but several R&D options may change the situation.* Electricity is the only major area of primary energy use that has not enjoyed significant efficiency improvements in the last 25 years, mostly because of the materials limitations that fix the upper temperature of the steam Rankine cycle and because of the parasitic requirements of environmental control measures (e.g., particulate removal and flu gas desulfurization). In parallel, demand for electricity has continued to grow to a point where its generation now consumes about one-third of the nation's primary energy. A significant breakthrough in the efficiency of electricity generation offers such high potential payoff that alternatives to the Rankine cycle deserve major emphasis. Promising options discussed in Chap. 3 include advanced aeroderivative combustion turbines, novel combined cycles, and fuel cells for use with natural gas or coupled with coal gasification and hot gas cleanup.

12. *Nuclear power is the most likely nonfossil source which can be deployed at much larger scale and at costs competitive with coal.* Although nuclear power already supplies about one-fifth of U.S. electricity, it faces significant constraints on expansion that would be needed to control the greenhouse effect. R&D to improve the performance of existing light water reactor technology, to develop advanced reactors with passive safety features, and to provide the means for better management of wastes may be a necessary prerequisite for public acceptance of such large-scale deployment.

13. *Biomass (woody and herbaceous plants) can be a significant source of liquids for transportation.* Advances in the productivity of growing plants for fuels and in the technology for converting the biomass to liquids promise to provide a source which could supply 10 to 15 quads/year of liquids. Such a source could provide a significant fraction of the energy needed for transportation, replacing fossil fuels.

14. *Photovoltaics, solar thermal electric, and wind have been improved enormously but are still expensive.* With successful R&D, these technologies might be able to produce electric power for $0.04 to $0.10/kWh at optimum geographic locations. In that case, they might provide peak power in conjunction with fossil or nuclear baseload plants. As stand-alone alternatives to fossil or nuclear plants, these technologies would require energy storage, which would significantly increase the costs of producing reliable power. Nevertheless, the potential for a breakthrough remains, particularly in photovoltaics. Recently,

Ogden and Williams (1989) have argued that the cost of electricity from amorphous silicon photovoltaics could become as low as \$0.02 to \$0.04/kWh dc; and, if so, it could be used to produce hydrogen by electrolysis in the desert Southwest. The hydrogen is then both the mechanism for energy storage and the energy carrier to be pumped around the country.

15. *Fusion energy R&D is making significant progress, but a prototype power plant is still decades away.* This potentially inexhaustible energy source has been under development for more than 30 years. The research community generally agrees that a machine which demonstrates net power production can be built. International collaboration may be the best route to such a demonstration. Fusion has significantly fewer environmental and safety challenges than fission; furthermore, it might be used to breed fuel for fission reactors, providing a potential alternative to fission breeders.

16. *More emphasis on technology demonstration will accelerate the adoption of new technologies.* Recent energy surpluses and low oil prices have eliminated much of the incentive for commercializing new technologies. The recent tendency of the U.S. financial system to focus on short-term investments has made the high-cost, long-term investments associated with commercializing many energy technologies even more unattractive. The critical importance of proven reliability to adoption of energy technologies means that arrangements must be found which allow commercial-scale technologies to be built and thoroughly tested under field conditions. Only proven performance will facilitate widespread commercial use of new or improved technologies. Much more active private-public sector collaboration and cost sharing are needed.

17. *R&D on decision making and measuring the conditions of social acceptance may improve the development process.* The deployment of new energy supply facilities may depend on developing better approaches to social decision making. Generally, such facilities are not without environmental and social impacts and may not be without health or safety risks. Research to learn better methods to accommodate public concerns and to mitigate or compensate for impacts could improve the prospects for deployment. Also, research may yield techniques for measuring the conditions of social acceptance. If these conditions can be reliably measured, the resulting data could be used as feedback into the R&D to improve the technology development process.

18. *Much of our optimism about the potential for better energy technologies derives from the promise of progress in related areas of science and cross-cutting technologies.* Revolutionary developments in materials science, in computing and microelectronics, and in biotechnology seem certain to make profound changes in the ways we transform, carry, and use energy. The possibilities range from high-temperature superconducting devices, such as long-distance power transmission lines, to bioengineered plants for liquid fuels, to smart controls for energy services in our homes and industries. The potential seems enormous.

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Appendix A
R&D Opportunities Identified in the Supply and End-Use Areas

This appendix lists research and development (R&D) opportunities identified in the energy supply and end-use areas. Teams of ORNL staff were organized in several areas of energy supply and end-use technology. Each team produced a report (see Vol. 2, Parts 1 and 2). The list of R&D opportunities in this appendix was compiled by reviewing the team reports.

Sources and Energy Carriers

1. FOSSIL

   1.1 CRUDE OIL

   Conventional Production
   - Exploration technology
   - Production technology
     - Geologically targeted infill drilling
     - Horizontal drilling
     - Deepwater production
     - Arctic production

   Enhanced Oil Recovery
   - Thermal recovery
   - Miscible flooding
   - Chemical flooding
   - Microbial

   Unconventional Production
   - Tar sands
   - Heavy oil

   1.2 GAS

   Conventional Production
   - Exploration technology
   - Production technology
     - Advanced drilling technology
     - Advanced logging technology
     - Deepwater production
     - Arctic production

1.2 GAS (*continued*)

Enhanced Gas Recovery

Unconventional Production
- Tight sands
- Coal seams
- Devonian shale
- Geopressured brines

1.3 COAL

Matching Chemical and Physical Properties of Coals to Optimize Process Design and Control

Preparation
- Better grinding and handling
- Advanced cleaning
- Waste disposal (e.g., fluidized bed combustion)

Direct Combustion
- Oil substitutes
  - Micronized coal
  - Coal/liquid slurry
- Fluidized bed
  - Atmospheric fluidized bed combustion
  - Pressurized fluidized bed combustion
- Reduction of oxides of sulfur and nitrogen
  - Wet or dry scrubbing
  - Catalytic reduction of nitrogen oxides
  - Sorbent injection
- Combustion systems
  - With refuse or biomass
  - Slagging combuster
  - Staged combustion
  - Better combustion-reaction modeling techniques
  - Better diagnostics and control
  - Computer-assisted design of coal retrofit burners
  - Combustion enhancement
- Better solids handling systems (erosion and clog resistant)

Gasification
- Separations
  - Hydrogen
  - Oxygen
  - Hot gas cleanup
- High-Btu gas production
  - Improved acid gas removal
  - Improved methanation

Gasification *(continued)*
- Bioprocessing
- In situ
- Nuclear process heat
- Integrated coal gasification combined cycle (e.g., use of steam-injected gas turbines, intercooled steam-injected gas turbines, fuel cells, hot gas cleanup)

Liquefaction
- Indirect (see gasification)
- Direct
  - Catalysts
  - Separations
- Bioprocessing
- In situ

1.4 SHALE OIL
- Retorting
  - Surface
  - In situ
- Refining
- Solid waste management
- Process water cleanup

1.5 CARBON DIOXIDE EFFLUENT SEQUESTERING

2. NUCLEAR FISSION

2.1 IMPROVING LIGHT WATER REACTOR TECHNOLOGY
- Reliability
  - Materials
  - Components
  - Robotics
- Safety
  - Diagnostics
  - Instrumentation
  - Controls
- Life extension
- Advanced light water reactor
  - Advanced pressurized water reactor
  - Advanced boiling water reactor

2.2 WASTE MANAGEMENT
- High level
- Low level
- Decommissioning

2.3 PASSIVELY SAFE ADVANCED REACTOR CONCEPTS
- Modular high-temperature gas-cooled reactor (MHTGR)

2.3 PASSIVELY SAFE ADVANCED REACTOR CONCEPTS (*continued*)

- Liquid metal reactor [sodium advanced fast reactor (SAFR), power reactor inherently safe (PRISM), integrated fast reactor (IFR)]
- Process inherent ultimate safety (PIUS) reactor

2.4 UNDERSTAND CONDITIONS TO IMPROVE PUBLIC ACCEPTANCE

2.5 RESOURCE EXTENSION

- Advanced enrichment techniques
  - Atomic vapor laser isotope separation (AVLIS)
- Recovery from lower grade resources
  - Seawater uranium
  - Chattanooga shale
- Nuclear breeding
  - Fusion-fission fuel factory
  - Breeder reactors
    - Liquid metal reactor
  - Accelerator breeder

2.6 TECHNOLOGIES TO DISCOURAGE PROLIFERATION AND DIVERSION

3. RENEWABLES

3.1 HYDRO

- Resource extension technologies
  - Free-flow turbine
  - Ultralow head turbine
- Environmental Management
  - Methods of assessment of flow on fish
  - Bypass devices for downstream migrants

3.2 BIOMASS

- Feedstock development
  - Terrestrial
  - Aquatic
- Materials handling
  - Harvest
  - Collect
  - Transport
  - Store
- Conversion
- Gasification
  - Hydrolysis/fermentation
  - Combustion
  - Chemical Feedstock

3.3 MUNICIPAL SOLID WASTE

- Collection
- Separation

3.3 MUNICIPAL SOLID WASTE (*continued*)

- Recycling
  - Secondary
  - Tertiary
  - Quaternary
- Landfill gas
  - Improved methods to characterize and optimize gas recovery
- Refuse-derived fuel

3.4 WIND

- Assessment of axis configuration
- Application of advanced power electronics
- Improved rotor materials
- Siting technology
- Generator research
- Improve airfoil design
- Turbine micro siting
- Wind hybrid systems
- Noise reduction
- Power station design

3.5 SOLAR THERMAL ELECTRIC

- Heliostats
- Central Receiver
- Parabolic Disk
- Trough

3.6 SOLAR PHOTOVOLTAIC

- One sun
  - Crystalline silicon
  - Amorphous silicon
  - Other thin films ($CuInSe_2$)
  - Multijunction
- Concentrating
  - Crystalline silicon
  - Multijunction
  - Copper indium telluride
  - Gallium arsenide
- Advanced automated manufacturing
- Photo electric chemical processes

3.7 GEOTHERMAL

- Hydrothermal
- Corrosion-resistant materials
- Effluent treatment
- Hot dry rock
  - Improved fracturing
  - Advanced drilling

3.7 GEOTHERMAL (*continued*)
- Geopressure
  - Experiment with existing wells
- Magma
  - Advanced drilling technologies
- Resource analysis and characterization

3.8 OCEAN ENERGY SYSTEMS
- Wave
- Tidal
- Ocean thermal energy conversion

4. FUSION

4.1 REACTOR SYSTEMS
- Magnetic
- Inertial

4.2 LOW ACTIVATION MATERIALS

4.3 FUEL CYCLE
- Lithium
- Tritium management

4.4 FISSILE FUEL BREEDER

5. ELECTRICITY

5.1 LEAST-COST UTILITY PLANNING METHODS

5.2 FUEL CELLS
- Phosphoric acid
- Molten carbonate
- Solid oxide
  - Monolithic oxide
  - Tubular oxide
- Proton exchange membrane

5.3 STORAGE
- Advanced batteries (e.g., Na/S, Li/FeS_2, Zn/Br, Zn/Cl)
- Superconducting coils
- Hydrogen
- Aluminum/air fuel cell
- Thermal
- Compressed air energy storage
- Flywheels

5.4 SUPERCONDUCTIVITY
- Energy storage

5.4 SUPERCONDUCTIVITY (*continued*)

- Transmission
- Distribution
- Transformers
- Generators
- Motors

5.5 TRANSMISSION AND DISTRIBUTION

- Automation
- High-voltage dc and ac
- Multiphase ac
- Amorphous metals for transformers and motors
- Better dielectric materials

5.6 LOAD MANAGEMENT

- Smart buildings
- Rate design
- Heat and cool storage
- Industrial load management
- Incorporating non-utility sources

5.7 POWER ELECTRONICS

5.8 ADVANCED CONVERSION

- Steam-injected gas turbine
- Intercooled steam-injected gas turbine
- Fuel cell
- Kalina cycle
- Higher temperature steam cycle
- Magnetohydrodynamics
- Combined cycle
- Alkali metal thermoelectric converter
- Thermionic converter

5.9 COGENERATION (see 7.9 and 8.9)

6. HYDROGEN

6.1 PRODUCTION

- Better electrolysis
  - Water vapor electrolysis
  - Reverse fuel cell
- Biophotolysis
- Chemical photolysis
- Thermochemical

6. HYDROGEN (*continued*)

6.2 STORAGE
- Absorption on activated carbon
- Liquefaction
- Pressurized
- Hydrided

6.3 PIPELINE RESEARCH

Energy Use Technologies

7. BUILDINGS

7.1 MANUFACTURED BUILDINGS AND COMPONENTS
- Automation in construction
- Integrated wall/window units
- Research on joints and sealants

7.2 AFFORDABLE HIGH-TECHNOLOGY HOUSING

7.3 COMPUTER-ASSISTED DESIGN

7.4 BUILDING CONTROL SYSTEMS
- Advanced computer technology
- Networks with utilities

7.5 ENVELOPES
- Building systems
  - Advanced wall systems
  - Foundations
  - Roofs
  - Use of mass
- Materials
  - Advanced insulating concepts and materials
  - Windows with electrically switchable optical property
  - Substitutes for CFCs in insulating materials

7.6 EQUIPMENT
- Thermally activated heat pumps
  - Long-lived heat engine drivers
  - Better pumps, valves, and controls
  - Corrosion-resistant high-temperature heat exchangers
  - Coupling with desiccant cooling
- Electric heat pumps
  - Continuous modulation
  - Improved controls and diagnostics
  - Chlorofluorocarbon substitutes

7.6 EQUIPMENT (*continued*)

- Ventilation in tight buildings
  - Heating, ventilating, and air conditioning comfort meter
  - Smart controls
- Lighting advances
  - Isotope enrichment
  - Two photon phosphors
  - Magnetic fields
- Refrigeration
- Superconductor applications

7.7 ENVIRONMENTAL ISSUES

- Chlorofluorocarbon substitutes
- Indoor air quality

7.8 EXISTING BUILDING EFFICIENCY IMPROVEMENTS

- Develop better institutional methods to promote adoption

7.9 INTEGRATION OF BUILDINGS INTO THE COMMUNITY

- Improved district heating and cooling
- Advanced cogeneration for large buildings

7.10 SOLAR TECHNOLOGIES IN BUILDINGS

- Photovoltaics
- Heating
- Cooling

8. INDUSTRY

8.1 CHEMICALS

- Catalysts
- Electroprocessing
- Sensors and computer control
- Separations
  - Membrane
  - Supercritical fluid extraction
  - Continuous freeze concentration
- Heat-flow optimization
  - Pinch-point analysis
- Combustion heater optimization

8.2 REFINING

- New hydrocarbon conversion technologies
- Waste heat recovery/energy cascading
- Waste utilization
- Separations
- Improved catalysts
- Sensors

8.2 REFINING (*continued*)

- Energy management systems
- Process flexibility to respond to crude changes

8.3 ALUMINUM

- Carbothermic reduction of ore or alumina
- Aluminum sulfide electrolysis
- Alcoa process
- Permanent anode
- Wetted cathode

8.4 STEEL

- Scrap beneficiation/purification
- Advanced ironmaking processes
- Advanced ore to steel processes
- Advanced scrap to steel processes
- Advanced casting
- Sensors and controls
- Advanced refractories

8.5 PULP AND PAPER

- Chemical pulping
- Paper/fiber recycle
- Mechanical pulping
- Papermaking
- Advanced pulping technologies
- Increased tree cellulose content
- Decreased tree lignin and hemicellulose content

8.6 AGRICULTURE

- Increased productivity with decreased per-unit inputs (especially decreased mineral fertilizer by increased biological nitrogen fixation)
- Improved field operations (e.g., "smart" tillage)
- Improved irrigation efficiency and water usage efficiency
- Animal biotechnology
- Plant biotechnology

8.7 REJECT HEAT RECOVERY

- Heat-flow optimization
- Efficient heat exchangers
- High-temperature thermal storage
- High-lift heat pumps

8.8 RECYCLE AND UTILIZATION OF WASTES

- Improved separation
- Waste utilization
- Waste characterization

8.9 COGENERATION

Small- to medium-sized systems
Flexible electricity to steam ratio
Coal-fired diesels

9. TRANSPORTATION

9.1 AUTOMOBILES AND LIGHT TRUCKS

- Gas turbine
- Low-heat-rejection engine
- Advanced materials for heat engines
- Flexible fuel vehicles and alternative fuel vehicles
- Optimize match between fuels and engines
- Direct injection stratified charge—solve emission problems
- Two-stroke engine—solve emission problems
- Automotive diesel with low emissions
- Continuously variable transmission
- Electric vehicles
  - Advanced batteries
  - Fuel cells
- Stirling engine
- Reduce drag
- Reduce tire rolling resistance
  - Tire pressure indicators
- Improved lubricants
- Lightweight, high-strength materials

9.2 HEAVY TRUCKS/BUSES

- Low-emissions heavy-duty engine
- Adiabatic turbocharged, direct-injection diesel
- Gas turbine
- Rolling resistance reduction
- Reduced drag

9.3 AIRCRAFT EFFICIENCY IMPROVEMENT

- Advanced aerodynamics
- New materials
  - Thermoplastics composition
  - Al-Li alloy
- Ultra bypass engines
- Distributed electrical control systems
- Computer-assisted flight management
- Electrohydrostatic activators

9.4 ADVANCED TRAFFIC SYSTEMS

- Automated dynamic traffic control
- Improved guideways
- Electric induction systems

9.5 HIGH-SPEED TRAINS

Appendix B
R&D Opportunities Identified in the Crosscutting Areas

This appendix lists R&D opportunities identified in the crosscutting areas. Teams of ORNL staff were organized in several areas of crosscutting science and technology. Each team produced a report (see Vol. 2, Part 3). The list of R&D opportunities in this appendix was compiled by reviewing the team reports.

1. MICROELECTRONICS/ADVANCED COMPUTING/SENSORS

- Smart Control Systems
  - Integrated sensors and processing
  - Distributed systems
  - Software

- Sensors
  - Specific measurements
    - Temperature
    - Pressure
    - Flow
    - Force/torque
    - Density
    - Viscosity
    - Humidity
    - Electromagnetic flux
    - Chemical
      - Indoor air quality
      - Specific electrodes
    - Motion/vibration
    - Proximity/location
  - Chip integrated sensors
  - Micro sensors
  - Sensors for hostile environments
  - Sensors embedded in structure
  - Signal transmission
    - Wire
    - Fiber optics
    - Electromagnetic (RF, microwave)
    - Ultrasonic
    - Optical (noncontact, IR)
  - Signal processing
    - Digital processors
    - Analog processors
    - Filters
    - Logic devices

Signal processing (*continued*)
- Sensor drift detection
- Displays
  - Industrial
  - Consumer
  - Microscopy
  - Human factors

Power Electronics
- Solid state
  - Switching
  - Motor controls
  - Larger, high-quality Si wafers
  - GaAs single-crystal films on Si substrates
- Computer-aided design tools
- Conducting polymers

Robotics
- Sensors
- Controls
  - Distributed
  - Modeling/software
  - Real-time/faster-than-real-time
- Communications
  - Remote
  - Effects of delays
  - Local intelligence
  - Autonomy
  - Machine intelligence
  - Actuators and control devices
    - Electronic power control
    - Stepping motors
  - Electronic systems

2. MATERIALS

High-Temperature Alloys
- Refractory metal alloys
- Intermetallic compounds

Structural Ceramics
- Fiber-reinforced ceramics

High-Temperature Superconducting Ceramics
- Inventing a practical power conductor

Corrosion/Erosion Resistant Materials
- Surface modification through ion implantation
- Ceramic coatings on metals

2. MATERIALS (*continued*)

Fiber-Reinforced Plastics
- Higher strength
- Higher temperatures
- Higher strength to weight ratio

Reduced Friction and Wear (Tribology Research)

Novel Applications
- Better heat, cold and fuel storage materials
- Better containment materials for radioactive and toxic wastes
- Polymer conductors
- Electronic ceramics
- Sensor materials

Materials by Design

3. BIOTECHNOLOGY

Microbially Enhanced Oil Recovery

Bioprocessing of Coal
- Sulfur removal
- Microbial solubization
- In Situ processing
- Waste treatment

Commodity and Specialty Chemicals

Hydrogen from Algal Water Splitting

Oil Substitutes from Algae and Oil-Producing Plants

Biofixation of Carbon Dioxide
- Improve Rubisco (Ribulose-bisphosphate carboxylase/oxygenase) by speeding up the catalytic fixation reaction or by making it more specific for CO_2 reduction

Biobased Materials

Methane from Landfills

Bioconversion of lignin, hemicellulose, and cellulose to fuels and useful chemicals such as thermoplastics

Understand Risks of Genetic Engineering

Genetic Research

Understanding synergisms between several microbial organisms

Genetic Research (*continued*)

Site-directed mutagenesis for redesign of proteins

Low-moisture biofeedstocks

Chemically reduced biofeedstocks

Micro-organisms which will work in severe environments

Immobilization of microorganisms and enzymes (e.g., on high surface area solids) to create high-productivity bioreactors

Enzyme technologies for use in organic solvents

4. SEPARATIONS

Major energy opportunities are to replace distillation, drying, and evaporation with less energy intensive processes.

Fundamental research on interfacial phenomena, selectivity, mathematical modeling, obtaining critical property information. chemistry of dilute solutions, system design and control

Membranes

Developing membrane separations (e.g., oxygen from air, hydrogen from oxygen, CO_2 from flue gas, nonaqueous applications)

Develop membranes that will work over broader range of temperatures and chemical conditions

Develop bio-mimetic membranes which mimic cellular separations

Improve the theory of membrane separation

Extraction

Supercritical fluid extraction research

Develop theory for polar materials and or role of additives in extraction

Theoretical design of extractants

Effects of external fields on extraction (e.g., for superconducting magnets)

Laser Isotope Separation Applied to Other Than Uranium

Ultrapurification Techniques—waste treatment; clean processes

Separation of Biological Cells (e.g., affinity chromatography and affinity solvent extraction)

Recovery of Uranium, Lithium, Deuterium, and Other Elements From Seawater (Also, fresh water and salt)

Removing Organic Sulfur from Coal

High-Efficiency Particle-Gas Separators to Operate at High Temperatures

Investigate High-Temperature Superconductor Magnets Applied to Separation (e.g., pretreatment of water, solid waste, chemicals)

5. COMBUSTION SCIENCE

Common R&D Needs
- Nonintrusive diagnostics
- Fundamental measurements/analysis
  - Flame and sorbent chemistry
  - Turbulence and mixing
- Combustion engineering/control
  - "Smart" control systems-sensors/computers
  - Improved flue gas instruments (sensors)
  - Combustion enhancement techniques
    - Atomization
    - Ignition
    - Catalysis
    - Membrane separation of oxygen (possible?)
    - Thermal barriers
    - Fuel modifications

Fuel Switching
- Developing methods for using micronized coal or coal slurries in oil and gas boilers without NO_x and SO_2 emissions by preconditioning coal to remove pyrite and ash and developing combustion simulation models for custom designing each conversion

Steam Generation
- Complete FBC development
- Develop effective direct sorbent injection techniques and new sorbents
- Basic understanding of how SO_2 and NO_x are produced and captured.
- Develop better post-combustion treatments (i.e., more efficient sorbents with less trouble-some by-products—for example, cyanuric acid for NO_x reduction; use of chelates in wet scrubbing as in the ARGONOX process

Internal Combustion

Problem	Solutions/discoveries
Engine knock	Fuel modification Combustion alteration (including use of stratified charge instead of homogeneous charge)
Lean limit	Fuel additive Perfect stratified-charge combustion
Particulate emissions	Fuel modification Enhanced mixing in cylinder Accelerate oxidation of particulates (as by catalyst)
NO_x emissions	Low-temperature, rapid combustion (as by catalyst) Simple postcombustion treatment

5. COMBUSTION SCIENCE (*continued*)

Wet Oxidation

Investigate for treatment of hazardous wastes; produces very low SO_2 and NO_x but also works at low temperatures (600°F)

Incineration

Combustion control for variable quality fuel

6. GEOSCIENCES

Oil and Gas

Enhanced oil recovery
Detection of subtle stratigraphic traps
Recovery of unconventional natural gas resources
Understanding the evolution and structure of sedimentary basins and methods of hydrocarbon entrapment
Storage of strategic reserves of crude oil
Minimization of groundwater impacts from abandoned wells
Protection of fragile lands during extraction of resources
Management of liquid wastes from oil and gas wells

Coal

Prediction of coal quality as controlled by:
Depositional environment and age of coal-producing organics
Diagenic and postdiagenic geological processes
Evaluation of coal organic constituents (macerals)
Influencing liquefaction processes
Improved extraction and reclamation methods
Improved data base for relating coal characteristics to end-use requirements
Ash utilization and disposal
Heavy metal recovery from ash and mine wastes

Nuclear

Basin studies and rock heterogeneity of sedimentary strata for exploration, development and resource base assessment
Geology and geochemistry of uranium migration and accumulation in natural systems and application to solution mining
Global resource assessment
Robotic deep mining technology
Low-level waste disposal technology
High-level waste disposal technology
Mill tailings disposal technology
Waste vitrification technology

Basic Research on Structure and Processes of the Earth's Crust

Improved understanding of the behavior of subsurface organic and inorganic fluids in rocks
Three-dimensional characterization of the internal properties and structure of rock bodies
In-situ measurement in high-pressure and high-temperature environments in deep boreholes

Basic Research on Structure and Processes of the Earth's Crust *(continued)*
- Modeling crustal structures and processes
- Testing crustal models through scientific drilling
- Exploring the range of hydrocarbon generation in time and space

Geothermal
- Spatial heterogeneity of geothermal reservoirs, especially in fracture-dominated regimes
- Laboratory investigation of physical and chemical properties of fluids and rocks
- Resource assessment and environmental impact of geothermal energy
- Development of techniques to produce adequately fractured systems

Oil Shale
- Mapping of oil shale microfacies
- Basic reactions in pyrolysis of oil shale kerogens
- Behavior of granular solids
- Physical properties of rock
- Environmental problems related to an oil shale industry
- Sulfur and nitrogen geochemistry of oil shale

Hydroelectric
- Dissolved oxygen management technology
- Dam reclamation technology

7. EFFLUENT MANAGEMENT

Develop Useful Products from Waste stream

Develop Waste Forms that Reduce Disposal Capacity and Costs

R&D to Improve the Durability of Solid Waste Forms

8. DECISION MAKING AND MANAGEMENT

Development of Effective Mechanisms for Feeding Information About Social/Risk Acceptance into the Energy Technology R&D Process

Research on Organizational Decision Making Under Uncertainty (e.g., least-cost planning)

Research on How Energy Technologies Penetrate Markets

Research on Processes for Voluntary "Translocal" Cooperation to Meet Broad Social Needs Related to Energy and the Environment (e.g., CO_2)

Research on the Effective Transfer of Publicly Funded R&D into Commercial Use

Research on Decision Making Related to Risk

8. DECISION MAKING AND MANAGEMENT *(continued)*

Investigations of Community-Based Risk Analysis and Management Approaches (e.g., community involvement and power sharing)

Research on Energy Technology Markets in Less-Developed Countries

Appendix C
Reducing CO_2 Emissions

In this appendix, we investigate in a preliminary way the contributions that improved energy efficiency and nonfossil energy sources could make towards reducing worldwide emissions of CO_2 from combustion of fossil fuels. In stating the problem this way, we bypass consideration of deforestation as a source of increasing atmospheric CO_2. As noted in Chap. 2, the annual net reduction (losses minus gains) of carbon in the terrestrial biosphere, including organic carbon in soils, may be as much as one-half the carbon release (as CO_2) from burning fossil fuels. Any serious effort to restrict CO_2 emissions would involve measures to limit net losses of biomass as well as fossil-fuel emissions. Nevertheless, we confine our discussion in this appendix to the question of reducing CO_2 emissions from fossil fuels.

As a preamble to this discussion, we first take note of probable differences in trends of future CO_2 emissions by different groups of countries. For this purpose, we divide the world—like Gaul—into three parts: (1) the industrial market economies, as represented by the Organization of Economic Cooperation and Development (OECD), hereafter referred to as Group A; (2) the industrial centrally planned economies (CPEs), that is, the USSR and East Europe, hereafter referred to as Group B; and (3) the rest of the world, comprising mainly the developing economies of Latin America, Africa, and Asia (including China), and hereafter referred to as Group C.

In Figs. 4.1 and 4.2, we saw that trends in overall energy consumption and in oil consumption have been quite different in these three groups of countries over the past 15 years. Not surprisingly, a similar pattern is evident if one looks specifically at CO_2 emissions (see Fig. C.1). In the decade 1977-87, CO_2 emissions in the OECD countries (Group A) stayed essentially constant (see Table C.1); emissions by Group B countries (industrial CPEs) increased over the decade at an average annual rate of nearly 2%/year; and emissions from the rest of the world (Group C) increased at more than 4%/year, which is close to the worldwide rate of increase that prevailed in the two decades prior to 1973 (i.e., about 4.5%/year average). It is quite possible that Group A emissions will again increase in the coming years, as they have shown signs of doing in 1987 and 1988; and one might expect the higher rates of increase in the other countries to moderate somewhat as time goes by. Nevertheless, it is reasonable to suppose that emissions by the latter two groups, and especially by Group C (developing countries and newly industrialized countries) will increase relative to emissions from the OECD countries.

These expectations are embodied in three highly simplified examples, shown in Fig. 4.4, in which future CO_2 emissions are represented by simple exponential functions, starting from the projected 1990 emission rates that are listed in Table C.1. Because the simple exponential behavior should not be expected to continue unchanged over so many years, the illustrations in Fig. 4.4 are increasingly unrealistic for the later years. Nevertheless, two important points are highlighted by Fig. 4.4: (1) OECD emissions will be less prominent in worldwide emissions in future than in the past; indeed Group C emissions may surpass Group A emissions within a couple of decades; and (2) if there is to be any hope of stabilizing worldwide CO_2 emissions at anything like current levels, let alone actually decreasing the world total, the industrial countries would have to decrease their emissions quite sharply—not a trivial task while maintaining economic growth.

In the remainder of this discussion, we focus on this last point: reduction of CO_2 emissions in industrial countries, and specifically in the United States. We explore the efficacy of two approaches for reducing future CO_2 emissions: (1) improved efficiency of energy use (conservation); (2) greater use of nonfossil energy sources; and (3) both of these together. We need to compare four scenarios representing future U.S. energy use and CO_2 emissions with and without higher efficiency and with and without greater use of nonfossil sources. For reference cases, we choose a mid-range projection

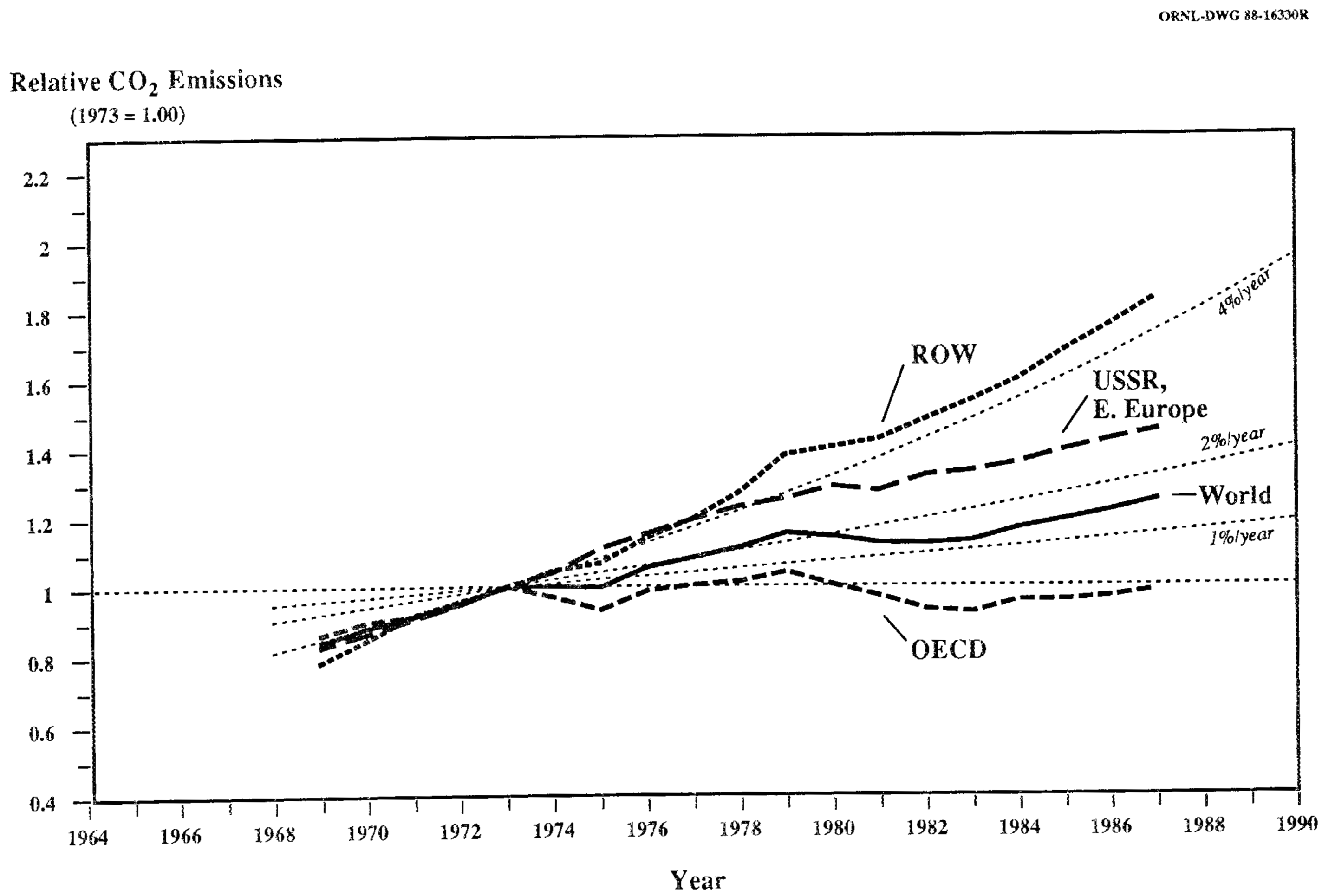

Fig. C.1. Relative CO_2 emissions by various nation groups (1973 = 1.00): Organization for Economic Cooperation and Development (OECD) nations; USSR and East Europe; and the rest of the world (ROW). *Source*: Computed from data in *BP Statistical Review of World Energy*, British Petroleum Company, June 1988.

Table C.1. CO_2 emissions, 1977-87 (GtC/year) and average growth rates (%/year)

Country group	Year	Carbon emissions from Oil	Gas	Coal	Total	Assumed annual emissions in 1990
A	1977	1.405	0.416	0.689	2.510	(2.5)
	1987	1.209	0.419	0.856	2.484	
	1987/77, ratio	0.860	1.007	1.242	0.990	
	Average, %/year	−1.50	0.07	2.17	−0.10	
B	1977	0.384	0.192	0.645	1.221	(1.6)
	1987	0.419	0.353	0.713	1.485	
	1987/77, ratio	1.091	1.839	1.105	1.216	
	Average, %/year	0.87	6.1	1.00	1.96	
C	1977	0.386	0.057	0.496	0.939	(1.6)
	1987	0.514	0.115	0.818	1.447	
	1987/77, ratio	1.332	2.018	1.649	1.541	
	Average, %/year	2.86	7.0	5.00	4.32	
World	1977	2.175	0.666	1.830	4.671	(5.7)
	1987	2.142	0.887	2.387	5.416	
	1987/77, ratio	0.985	1.332	1.304	1.159	
	Average, %/year	−0.15	2.87	2.66	1.48	

of future U.S. energy use and a case representing very deep reductions in energy use per unit of economic output (E/GNP). For the first of these, we take the Base Case from the Edmonds-Reilly model, as discussed in Sect. 2.4 and illustrated in Figs. 2.21 and 2.22 (Edmonds and Reilly 1986). For the present purpose, we use only the U.S. portion of the Base Case (which covers the whole world). The Base Case is calculated by the model with median values of all model parameters. The U.S. gross national product increases at 3%/year during the period 1975 to 2000, 2.3%/year from 2000 to 2025, and 2%/year from 2025 to 2050, reflecting in part an assumed decline in the rate of population growth. U.S. energy consumption increases less rapidly, rising from 70.5 quads in 1975 to 90 quads in the year 2000, 115 quads in 2025, and 142 quads in 2050. Thus, E/GNP decreases significantly even in this case, falling to 60% of the 1975 value in 2000, 43% in 2025, and 32% in 2050.

For the High Efficiency Case, we adopt the scenario of Williams, also discussed in Sect. 2.4 (Williams 1987). In this scenario, per capita GNP in the United States doubles between 1980 and 2020; GNP increases by a factor of 2.6, for an average growth rate of 2.4%/year. However, very large reductions are assumed in the energy required for almost all activities and processes, so that overall E/GNP in 2020 is only one-fourth (27%) as large as in 1980. This more than offsets the rising GNP, so that energy use decreases 30%, from 76 quads in 1980 to 53 quads in 2020.

These two cases, the Edmonds-Reilly (E-R) Base Case and the Williams High Efficiency Case are not "pure" cases for purposes of the intended comparison. The E-R Base Case already incorporates a significant improvement in energy efficiency, and both reference cases include a lot of nonfossil sources in their supply mix. We have modified the reference cases in two ways in order to

normalize the comparative influence of greater use of nonfossil sources.

Modification A: In both the E-R Base Case and the Williams High Efficiency Case, the supply mix is modified to reduce the contribution of nonfossil sources to a low level assumed to be achievable without R&D or further technical advances.

Modification B: In each case the supply mix is modified to expand the contribution of nonfossil sources to the extent assumed to be achievable with substantial R&D successes, technical advances, and realistic deployment schedules.

The assumed contributions from nonfossil sources are in two categories: (1) liquids from biomass, displacing oil in the transportation sector; and (2) nonfossil sources of electricity (nuclear, hydro, solar-electric, wind, geothermal) displacing mainly coal, but also oil and gas, in the electric utility sector. The assumed contributions are shown in Table C.2.

Note that we have assumed that 10 quads of liquid fuels can be produced in the United States from 20 quads of biomass, harvested on a sustained-yield basis. Our study's panel on biomass believes that potential production may be somewhat higher than this, but here we assume 10 quads. This production level is reached by 2020 and thereafter remains constant.

For hydroelectricity, we assume that an additional 47 GW of capacity could be brought into service, including remaining high-head sites and low-head sites, some of which already have impoundments not currently used to generate electricity. At an annual average capacity factor of 43%, which is typical for current hydro facilities, these additional plants would produce about 175 $\times 10^9$ kWh(e)/year. This would be added to about 300 $\times 10^9$ kWh(e)/year from existing facilities. (The 250 $\times 10^9$ kWh(e) generated in 1987 was unusually low because of persistent below-normal precipitation; it was the lowest since 1977, which was also a very dry year.) Although the incentives for developing this additional hydroelectric capacity would be greater in Circumstance 3 (serious greenhouse threat) than otherwise, we assume this increased hydroelectric output in Modification A as well as in Modification B on the grounds that little new technology would be required.

For nuclear power, there is a very important difference between Modification A and Modification B (minimal versus maximum use of nonfossil sources). For Mod A, we assume that no new orders will be placed for nuclear reactors in the United States. However, some of those still under construction will be completed, and installed nuclear capacity will level off in the 1990s at around 100 to 110 GW(e). Sometime after the turn of the century, retirement of older or less economical plants begins to reduce the aggregate generating capacity of U.S. nuclear plants on a schedule which we do not attempt to outline in detail. Nevertheless, with some life-extension measures, we assume that 80 GW(e) of nuclear plants will remain in 2020 from the "first nuclear era." We further assume a progressive increase in average capacity factors for nuclear plants, from 57% in 1987 to around 70% in 2020, permitting these 80 GW(e) to generate around 500 $\times 10^9$ kWh(e). By 2040, even with life extension measures, few of the twentieth-century nuclear plants remain, and we assume that these generate about 170 $\times 10^9$ kWh(e) in 2040.

For Mod B, we assume rapid deployment of a new generation of nuclear reactors based on Advanced Light-Water Reactor (ALWR) technology and on other passively safe concepts such as the Modular High Temperature Gas-cooled Reactors (MHTGR). It should be noted that only the ALWR could be ready for construction by 1995. We assume that the MHTGR could not be ready for commercial orders much before 2005. Under our assumptions, first orders are placed by 1995, the first new reactor is completed around 2005, and thereafter reactors are completed on an accelerating schedule. According to this schedule, 12 GW(e) of new capacity would be completed between 2005 and 2010, an additional 52 GW(e) in the period 2011 to 2015, 75 GW(e) in the period 2016 to 2020, 205 GW(e) between 2020 and 2030, and 305 GW(e) between 2030 and 2040, for a total of 649 GW(e) brought on line in the period 2005 to 2040. Completion rates are 15 GW(e)/year in 2016 to 2020, then increasing linearly to 35 GW(e)/year in 2040. It is worth noting that these construction rates are neither alarming nor unprecedented. From 1965 to 1985, the average annual rate of generating-capacity additions of all types in the United States was 23 GW(e)/year. From 1965 to 1975, the average rate

Table C.2. Assumed contributions of nonfossil sources

	1987 (Actual)	2020 A	2020 B	2040 A	2040 B
Liquids from biomass					
Quads of liquids	0	0	10	0	10
Quads of biomass	0	0	20	0	20
Electricity, 10^9 kWh(e) (quads)					
Nuclear	455(4.9)	500(5.3)	1500(16.0)	170(1.8)	4000(42.7)
Hydro	250(3.0)	475(4.6)	475(4.6)	475(4.6)	475(4.6)
Solar, etc.	12(0.3)*	25(0.3)	125(1.2)	25(0.3)	525(5.1)
Sum	717(8.2)	1000(10.2)	2100(21.8)	70(6.7)	5000(52.4)

*Low efficiency; approximately 17%.

was 27 GW(e)/year. Yet our postulated GNP in 2020 is nearly 4 times larger than in 1970 and by 2040 it is almost 6 times larger than in 1970. These capacity additions, plus remaining plants from the first era, generate 1500 billion kWh(e) in 2020 and 4000 billion kWh(e) in 2040.

Our assumptions regarding the other nonfossil sources of electricity (photovoltaics, solar thermal electric, wind, geothermal, tides, etc.) are more arbitrary. We make no attempt here to distinguish among them, treating them in the aggregate. The physical potential of these sources is very large. The economic potential may be more limited, and is not easy to predict. Together, these sources (plus wood and wastes) currently generate about 12 billion kWh(e)/year in the United States for distribution by electric utilities. This is about 0.5% of the U.S. total from all sources. We assume that by 2020, given sufficient incentives to do so (such as the greenhouse effect), this contribution could be increased by an order of magnitude, e.g. to 125 billion kWh(e)/year—about what was generated in 1987 by oil-fired units. This is equivalent to about 1.2 quads, and is by no means the maximum that could ultimately be generated by these sources. [It is also equivalent to about 28 GW(e) operating at an annual average capacity factor of 50%. However, some of these sources could not approach a 50% capacity factor, so the actual installed capacity would be much greater than 28 GW(e).]

We further assume that by 2040, the annual electricity generation from these other technologies could be increased to 525 billion kWh(e) (nearly as much as is currently supplied by nuclear power and hydropower combined), bringing the total from all nonfossil electricity generators to 5000 billion kWh(e), or about twice the present U.S. total from all sources. How this quantity is divided among the various nonfossil technologies (nuclear, hydro, photovoltaics, etc.) is actually immaterial for the resulting reduction in CO_2 emissions. However, we believe that the combined total of all the nonfossil sources, as determined by the time-dependent constraints discussed above, could probably not increase much more rapidly than we have assumed here.

Williams presents his "Low Energy Future for the United States" only for the year 2020 (Williams, 1987). However, efficiency cannot be improved without limit, and it isn't clear to us that the four-fold reduction in E/GNP represented in this scenario can be carried much further. If the economy

continues to grow after 2020, as we assume it will, one might expect a reversal of the downward trend in energy consumption that the High Efficiency case achieves for the period 1980 to 2020. In that case, the substitution of nonfossil energy sources for fossil fuels would be a necessary adjunct to efficiency improvement in any effort to limit CO_2 emissions. In short, Williams' "Low Energy Future" may not be a sustainable future beyond 2020 if it continues to rely primarily on fossil fuels to maintain economic growth. For this reason, we extended the comparisons to 2040. In order to project Williams' scenario to 2040, we projected disaggregated activities (home heating, hot water, appliances, commerical energy requirements, personal travel, highway freight, air transport, manufacturing, basic materials, etc.) according to Williams' prescriptions, including a continuing trend toward a less-energy-intensive mix of industrial activities, but retained the same energy intensities per unit activity as Williams postulated for 2020.

All of these considerations are brought together in Table 4.1, which shows electricity generation, total primary energy use, and CO_2 emissions for each of the four cases, for the years 2020 and 2040. The last column, Modification B' of the High Efficiency case for 2040, was added because the total electricity requirement in Mod B of the High Efficiency case was less than the assumed potential generation from nonfossil sources alone. We therefore considered a further substitution of electricity for fossil fuels in the buildings sector (replacing methane), and in the transportation sector (electric vehicles or electrolytic hydrogen fuel), up to the full exploitation of the nonfossil potential.

The CO_2 emissions for all these cases are shown in Fig. 4.3 in Chap. 4. The coefficients used to translate energy use in quads into CO_2 emissions are: for coal, 0.025 GtC/quad; for oil, 0.020 GtC/quad; for gas, 0.015 GtC/quad. These are not quite the same as those calculated by Rotty and Marland (1980). The principal difference is for oil. Rotty and Marland recommended 17.4 gC/MJ = 0.0184 GtC/quad, to allow for an estimated 8.2% of oil production that is not oxidized because it is used in the manufacture of long-lived products. Since our focus here is on substitutions for energy production and use, it is appropriate to use conversion factors based on 100% oxidation of the fuels.

In each of the comparisons (Modification A vs. Modification B for the E-R Base Case and similarly for the High Efficiency Case) we assumed the same distribution of final energy demand (i.e., the same quantity of fuels and the same quantity of electricity) in Mod B as in Mod A. In going from Mod A to Mod B, we substituted 10 quads of liquids (from 20 quads of biomass) for 10 quads of oil; and nuclear-, hydro-, and solar-electricity substituted for electricity generated with coal, oil and gas, to the extent shown in Table 4.1. For the E-R Base Case, it is clear that U.S. CO_2 emissions would rise continuously to a level almost twice as high in 2040 as in 1987. The reason, as noted above, is that efficiency improvements, as large as they are in this case, do not occur rapidly enough to offset growth in economic output. Furthermore, in the near term (out to 2020), nonfossil sources cannot be deployed fast enough in this case to keep CO_2 emissions from increasing. Later on, however, the nonfossil sources, according to our assumptions, could penetrate their markets deeply enough to return CO_2 emissions to the current level by 2040, despite a four-fold increase in GNP.

On the other hand, if the very large efficiency improvements envisioned by Williams could in fact be accomplished by 2020, then E/GNP would fall more rapidly than GNP increases and energy use (and CO_2 emissions) would decrease over time, at least until such time as further improvements in efficiency become more difficult or costly to achieve, while economic growth continues. At that time, which in our example is between 2020 and 2040, economic growth would again overwhelm efficiency improvements and energy use (and CO_2 emissions) would again increase with time. By then, however, nonfossil sources could begin to replace a major part of fossil-fuel requirements and, with their help, U.S. CO_2 emissions could continue to fall.

Thus, the issue boils down to these questions: How much and how rapidly will GNP increase? How much and how rapidly can the average energy intensiveness of various economic activities be reduced? How much will the composition of GNP continue to shift from the more-energy-intensive activities, like mining and heavy manufacturing, to less-energy-intensive activities, like information processing, health care, etc.? And how much and how fast could the services now provided by fossil

fuels be shifted to various nonfossil energy sources? Expressed in the resulting CO_2 emissions by the United States, the possibilities represented in Fig. 4.3 range from a two-thirds reduction to a two-fold increase in emissions over the next half-century. The steps required to achieve a substantial reduction in U.S. CO_2 emissions, if that should prove necessary, are (first) very large reductions in the energy intensiveness of activities throughout the U.S. economy, which would be most effective in the near term, and (second) large-scale substitution of nonfossil sources for fossil fuels in the longer term.

It should be noted that the level of nuclear power that is incorporated in Modification B of each case for the year 2040 is less than was expected fifteen years ago to be reached in the United States by the year 2000. Nevertheless, it is large enough to raise questions about uranium availability. We estimated cumulative natural uranium requirements for our postulated nuclear-power expansion on the assumption that all the reactors would use uranium with about the same efficiency as today's Light Water Reactors. That is, they would use less than 1% of the energy content of the uranium, if operated on a once-through fuel cycle, and about 1%, with recycle of Pu and U. Without recycle, cumulative natural uranium requirements would exceed 1 million metric tons by 2030 (1.3 million short tons of U_3O_8), and would reach 2 million metric tons of natural uranium shortly after 2040. Cumulative uranium consumption plus lifetime commitments for all reactors in operation would exceed 3 million metric tons of uranium (4 million short tons of U_3O_8) by 2040. At that time (2040), cumulative uranium consumption plus forward commitments would be increasing at about 92,000 metric tons of uranium (120,000 short tons of U_3O_8) per year.

We don't really know how much uranium can reasonably be expected to be available to the United States. In the past, quantities like 2 million to 4 million tons were thought to be potentially available in the United States from domestic sources not counting such low-grade sources as the Chattanooga shales and seawater, which contain vastly greater quantities of uranium. It is conceivable that these low-grade sources could be used. Furthermore, prospecting for uranium has been far less intensive in most of the rest of the world than in the United States. It seems likely that much larger amounts of uranium will ultimately be available in high-grade deposits worldwide than is presently acknowledged by the International Atomic Energy Agency and OECD's Nuclear Energy Agency. Also, it may become feasible to produce plutonium from natural or depleted uranium in accelerator-breeders or in fission-fusion hybrid machines. In short, we are not likely to "run out" of uranium.

Nevertheless, the conventional view of the uranium supply problem may still be the correct one: if nuclear power becomes a major energy source, eventually we will need breeder reactors. Our present sense of the problem is that that could occur as early as the second quarter of the coming century, that is, within the time horizon of this study.

In this analysis we have said nothing about relative costs. Our tacit assumption is that after internalizing the costs of waste management, decommissioning, and dealing with safety issues, nuclear power will still be more economical than renewables, and that in the case of Circumstance 3 (serious threat from the greenhouse effect), it will prove to be acceptable even with large-scale deployment. Of course, this may not turn out to be the case. It may be that society will choose to buy a more expensive set of renewable-energy technologies or that R&D may make renewables competitive.

We doubt that these possibilities will change our basic conclusion that reducing CO_2 emissions will be very difficult and will depend both on much-improved efficiency of energy conversion and use and on nonfossil energy sources. The costs will depend largely on the success of R&D.

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